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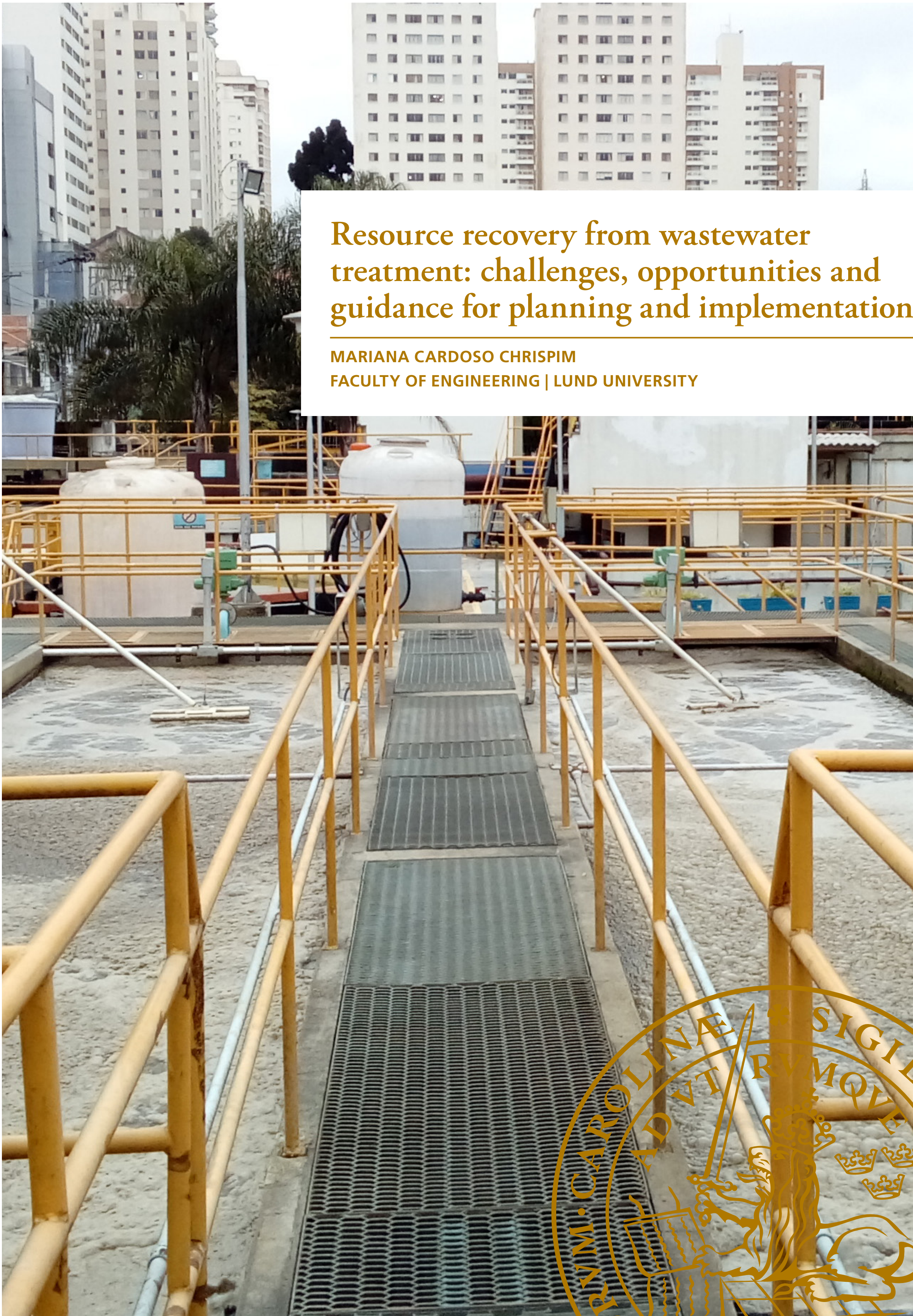

Resource recovery from wastewater treatment: challenges, opportunities and guidance for planning and implementation

MARIANA CARDOSO CHRISPIM
FACULTY OF ENGINEERING | LUND UNIVERSITY

Mariana C. Chrispim is an environmental manager with a master's degree in Public Health and concentration in Environmental Health (at the University of Sao Paulo-USP, Brazil). In her research, she has focused on analyzing the possibilities of resource recovery from wastewater treatment processes, addressing various aspects, seeking to facilitate the transition to a circular economy vision.

Most of the world megacities are in developing countries and face similar issues: water scarcity, water pollution, lack of provision of clean water, and safe disposal of wastewater. Thus, appropriate treatment and resource recovery solutions are effective water conservation measures. This thesis explores the potentials and limits of resource recovery in municipal wastewater treatment plants, particularly in large cities of developing countries, as well as offers guidance for planning and implementation. The information and knowledge presented here should be useful for government, managers, and researchers to guide further technological development, and support transition to sustainable and efficient wastewater treatment plants and sustainable cities.

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Resource recovery from wastewater treatment: challenges, opportunities and guidance for planning and implementation

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Mariana Cardoso Chrispim

LUND UNIVERSITY

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Box 118
SE-221 00 Lund, Sweden

Author(s) Mariana Cardoso Chrispim

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Abstract
Considering the current resources scarcity, Wastewater Treatment Plants (WWTP) should be adapted to become more sustainable. For example, it is possible to recover resources present in municipal wastewater. However, regional studies about integration of resource recovery processes at different scales or about the main barriers to implementation in developing countries are missing in the literature. Also, there is a need for planning methodologies to identify the most sustainable solution in each context. Understanding the current situation is an essential step to support planning and accelerate resource recovery implementation. To address these issues this thesis aims to guide planning, technology and policy development towards resource recovery from municipal WWTP in large cities of developing countries. This thesis presents a comprehensive knowledge base for wastewater treatment plant managers and decision-makers leading to a better understanding of resource recovery solutions and the actions needed to facilitate implementation. The methodology comprised critical literature reviews and two case studies. Secondary data from literature and primary data (obtained through questionnaires) were collected and analysed. Megacities in developing countries are analysed in the papers, with the focus on the Macrometropolis of Sao Paulo, which is the most populous area in the Southern Hemisphere. The current situation shows a low implementation of resource recovery practices in the region, and local conditions affect the implementation of water reuse, and nutrients and energy recovery. A framework consisting of eleven steps is proposed to support planning and decision-making on resource recovery from wastewater. This new tool was tested and can be applied by decision-makers in wastewater sector for better operation and management. Market, legislation, local economic development, and cooperation with stakeholders are relevant aspects covered in the analysis. There is a great potential to expand wastewater treatment integrated with nutrient and energy recovery strategies in developing countries. Potentials for phosphorus and energy recovery were estimated and some recovery scenarios are recommended. In conclusion, the findings can help planning and elaboration of resource recovery projects in wastewater treatment in urban areas and stimulate creation of public policies. The main research gaps identified in this thesis can guide further research and technological development in this field.

Key words Circular economy. Resource Recovery. Sewage. Planning. Water. Nutrient. Biogas. Developing countries. Urban areas

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This doctoral thesis is a result of a double degree agreement between the Division of Water Resources Engineering, Department of Building and Environmental Technology, Lund University, Sweden, and The Graduate Program in Sustainability, in the School of Arts, Sciences and Humanities, University of Sao Paulo, Brazil

Supervisor at Lund University:
Prof. Dr. Miklas Scholz

Supervisor at University of Sao Paulo:
Prof. Dr. Marcelo Antunes Nolasco

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To those who inspire me the most: my beloved grandmother and great friend Eunice (in memoriam), and my dearest mom Jeanette

Wastewater is only wastewater when we choose to waste it
(Michael J. Wilson).

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Abstract

Considering the current resources scarcity, Wastewater Treatment Plants (WWTP) should be adapted to become more sustainable. For example, it is possible to recover resources present in municipal wastewater. However, regional studies about integration of resource recovery processes at different scales or about the main barriers to implementation in developing countries are missing in the literature. Also, there is a need for planning methodologies to identify the most sustainable solution in each context. Understanding the current situation is an essential step to support planning and accelerate resource recovery implementation. To address these issues this thesis aims to guide planning, technology and policy development towards resource recovery from municipal WWTP in large cities of developing countries. This thesis presents a comprehensive knowledge base for wastewater treatment plant managers and decision-makers leading to a better understanding of resource recovery solutions and the actions needed to facilitate implementation. The methodology comprised critical literature reviews and two case studies. Secondary data from literature and primary data (obtained through questionnaires) were collected and analysed. Megacities in developing countries are analysed in the papers, with the focus on the Macrometropolis of Sao Paulo, which is the most populous area in the Southern Hemisphere. The current situation shows a low implementation of resource recovery practices in the region, and local conditions affect the implementation of water reuse, and nutrients and energy recovery. A framework consisting of eleven steps is proposed to support planning and decision-making on resource recovery from wastewater. This new tool was tested and can be applied by decision-makers in wastewater sector for better operation and management. Market, legislation, local economic development, and cooperation with stakeholders are relevant aspects covered in the analysis. There is a great potential to expand wastewater treatment integrated with nutrient and energy recovery strategies in developing countries. Potentials for phosphorus and energy recovery were estimated and some recovery scenarios are recommended. In conclusion, the findings can help planning and elaboration of resource recovery projects in wastewater treatment in urban areas and stimulate creation of public policies. The main research gaps identified in this thesis can guide further research and technological development in this field.

Keywords: Circular economy. Resource Recovery. Sewage. Planning. Water. Nutrient. Biogas. Developing countries. Urban areas.

Resumo

Considerando a atual escassez de recursos, as Estações de Tratamento de Esgotos (ETE) devem ser adaptadas para se tornarem mais sustentáveis. Por exemplo, é possível recuperar os recursos presentes no esgoto municipal. Entretanto, estudos regionais sobre a integração de processos de recuperação de recursos em diferentes escalas ou acerca das principais barreiras para a implementação em países em desenvolvimento estão faltando na literatura. Além disso, são necessárias metodologias de planejamento para identificar a solução mais sustentável em cada contexto. Entender a situação atual é uma etapa essencial para subsidiar o planejamento e acelerar a implementação da recuperação de recursos. Para abordar essas questões, esta tese tem como objetivo orientar o planejamento, o desenvolvimento tecnológico e de políticas públicas direcionados à recuperação de recursos em ETEs municipais de grandes cidades de países em desenvolvimento. Essa tese apresenta uma base de conhecimento abrangente para gestores e tomadores de decisão no tratamento de esgotos propiciando uma melhor compreensão das soluções de recuperação de recursos e das ações necessárias para facilitar a implementação. A metodologia consistiu em revisões críticas da literatura e dois estudos de caso. Foram coletados e analisados dados secundários a partir da literatura e dados primários (obtidos através de questionários). Megacidades em países em desenvolvimento são analisadas nos artigos, com foco na Macrometrópole Paulista, a área mais populosa do Hemisfério Sul. A situação atual mostra uma baixa implementação de práticas de recuperação de recursos na região, sendo que as condições locais afetam a implementação de práticas de água reúso, recuperação de nutrientes e de energia. Um framework (ferramenta com estrutura e procedimentos) que consiste em onze etapas é proposto para apoiar o planejamento e a tomada de decisões sobre a recuperação de recursos a partir do esgoto. Essa nova ferramenta foi testada e pode ser aplicada pelos tomadores de decisão no setor de esgoto para melhor operação e gestão das estações. O mercado, as legislações, o desenvolvimento econômico local, e a cooperação com as partes interessadas são aspectos relevantes abordados na análise. Há um grande potencial de expansão do tratamento de esgotos integrado com estratégias de recuperação de nutrientes e energia em países em desenvolvimento. Os potenciais de recuperação de fósforo e energia foram estimados e alguns cenários de recuperação de recursos são recomendados. Por fim, conclui-se que os resultados podem auxiliar no planejamento e na elaboração de projetos de recuperação de recursos no tratamento de esgotos em áreas urbanas e estimular a criação de políticas públicas. As principais lacunas do conhecimento científico identificadas nessa tese podem direcionar pesquisas futuras e o desenvolvimento tecnológico nesse tema.

Palavras-chave: Economia circular. Recuperação de recursos. Esgotos domésticos. Planejamento. Água. Nutriente. Biogás. Países em desenvolvimento. Áreas urbanas.

Popular summary

Conventional wastewater treatment systems cause environmental impacts, including energy consumption and solid waste generation (e.g., sludge), which pose challenges to cities. Based on recent technological knowledge, there is a need to adopt a new sanitation approach based on recovery of resources present in wastewater. Resource recovery is the production or extraction of any material or energy from the operations of wastewater treatment plants. However, regional studies about the integration of resource recovery processes at different scales or that have identified the main barriers to implementation in developing countries are missing in the literature.

The information and knowledge presented in this thesis should be useful for governments, managers, and researchers to guide further technological development, support transition to more sustainable and efficient wastewater treatment plants (WWTP) as well as sustainable cities. Consequently, resource recovery has a potential to provide environmental, social, and economic benefits to local communities (e.g., reducing water stress and improving well-being, and producing alternative source of fertilizer). Our results can provide guidance and support decisions at WWTP and regional levels considering technical, economic, and environmental aspects. The results can also be used by policymakers, managers, and other people working in this field to stimulate resource recovery implementation, for example, creating projects of energy recovery or educating and engaging local stakeholders through awareness of resource recovery importance. Therefore, the results represent valuable information for planning process about local conditions that can affect recovery technologies choice.

There is a high potential for resource recovery in developing countries, however, not well-explored so far as shown by the results. Phosphorus recovery technologies recommendations for the Latin America region are given based on the existing treatment infrastructure. The current challenges to phosphorus recovery are: lack of decision-making tools, WWTP size, market-value of recovered resources, economic incentives, economic feasibility, public acceptance, legislations, lack of an integrated approach, and personnel skill limitations. Most of these barriers were confirmed through the investigation of real cases in the Macrometropolis of Sao Paulo, where local legislations and incentives towards resource recovery are missing. Energy recovery implementation and local conditions are also investigated. The results indicated that all the assessed megacities (Sao Paulo, Cairo, and Mexico

City) need to strengthen their policies and subsidies related to climate change and energy recovery.

Most of world's megacities are in developing countries and face similar issues: water scarcity, lack of infrastructure, water pollution, high population density, lack of provision of clean water and safe disposal of wastewater. Thus, appropriate treatment, and resource recovery solutions such as reuse of treated wastewater is an effective water conservation measure.

This thesis focused on evaluating the current situation, problems, and potentials for improvement of resource recovery in urban areas, particularly of developing countries. The main scope was megacities of developing countries. This research includes two critical literature reviews on phosphorus and energy recovery challenges and opportunities. Also, the thesis includes two case studies in the Macrometropolis of Sao Paulo, the most populous area in Brazil. Data were collected from various sources: a survey with wastewater treatment utilities, national and regional databases, local regulations, and international literature. The reasons why resource recovery is still little implemented in wastewater treatment plants (particularly in developing countries) are explored.

In summary, this thesis addressed what needs to change to implement resource recovery strategies from wastewater sector, particularly in megacities of developing countries. A generic framework which includes eleven steps was proposed as a tool to facilitate planning and implementation. The framework application was tested and is considered an important measure to enhance resource recovery implementation. In addition, the creation of new business models and public policies, partnerships with key stakeholders, creation of networks, educational measures, development of market, reduction of investment and operational costs of recovery technologies, financing mechanisms and incentives are needed for promoting implementation.

Papers

Appended papers

I. **Chrispim, M.C.**, Scholz, M., Nolasco, M.A., 2019. Phosphorus recovery from municipal wastewater treatment: Critical review of challenges and opportunities for developing countries. J. Environ. Manage. 248, 109268. https://doi.org/10.1016/j.jenvman.2019.109268

II. **Chrispim, M.C.**, Scholz, M., Nolasco, M.A., 2020. A framework for resource recovery from wastewater treatment plants in megacities of developing countries. Environ. Res. 188, 109745. https://doi.org/10.1016/j.envres.2020.109745

III. **Chrispim, M.C.**, de Souza, F. de M., Scholz, M., Nolasco, M.A., 2020. A Framework for Sustainable Planning and Decision-Making on Resource Recovery from Wastewater: Showcase for São Paulo Megacity. Water 12 (12), 3466. https://doi.org/10.3390/w12123466

IV. **Chrispim, M.C.**, Scholz, M., Nolasco, M.A. 2021 (Manuscript submitted on January 11, 2021). Biogas recovery for sustainable cities: a review of enhancement techniques and key local conditions for implementation. Sustainable Cities and Society.

Author's contribution to the appended papers

I. The author conducted the literature review (searches and reading of the papers), wrote the full manuscript, prepared the figures and the set of tables, and revised the manuscript based on the co-authors feedback. The author also contributed to the manuscript revision and the responses to the reviewers' comments. The co-authors participated in discussions, revisions, and manuscript editing.

II. The author was responsible for the conceptualization, methodology, investigation, data collection, analysis, and framework creation. The author wrote the full manuscript, prepared the figures and tables and made the revisions. The second co-author contributed to the conceptualization. The co-authors participated in discussions, revisions, and manuscript editing.

III. The author designed the survey and methodology, conducted the investigation, and collected all the data for the framework application with the assistance of the second co-author. The author wrote the full manuscript, prepared the figures and tables, and reviewed the manuscript. The second co-author contributed to the revisions. The third and fourth co-authors (supervisors) contributed to conceptualization, participated in discussions, revisions, and manuscript editing.

IV. The author performed the literature review (searches and reading of the selected papers), conceptualization, developed the critical analysis, data collection and prepared the figures and tables. The author wrote the full manuscript and revised it based on the co-authors feedback. The co-authors (supervisors) contributed to discussions, minor editing, and proofreading.

Related publications not included in this dissertation

Journal articles

Chrispim, M.C., Nolasco, M.A., 2017. Greywater treatment using a moving bed biofilm reactor at a university campus in Brazil. J. Clean. Prod. 142, 290–296. https://doi.org/10.1016/j.jclepro.2016.07.162

Chrispim, M.C., Tarpeh, W.A., Salinas, D.T.P., Nolasco, M.A., 2017. The sanitation and urban agriculture nexus: urine collection and application as fertilizer in São Paulo, Brazil. J. Water, Sanit. Hyg. Dev. 7 (3), 455–465. https://doi.org/10.2166/washdev.2017.163

Book chapter

Chrispim, M.C., 2017. Evaluation of decentralized approaches to wastewater treatment systems as alternative to environmental impacts and indication of sustainable solution for water conservation in cities. Proceedings of the Regional Workshop Wastewater Treatment and reuse for metropolitan regions and small cities in developing countries. 1st ed. Göttingen: Cuvillier, 2017, v. 1. 140p.

Conference abstracts

Chrispim, M. C., Scholz, M., Nolasco, M. A. Resource recovery from wastewater treatment plants in megacities of developing countries: current status and potentials. In: Water Security and Climate Change Conference 2021, online event.

Chrispim, M. C., Nolasco, M. A., Scholz, M. Final Disposal and Valorization of Sewage Sludge: Current Practices and Ongoing Research. In: 9th International Workshop Advances in Cleaner Production ´´Towards Sustainable energy-water-food nexus: the contribution of a cleaner production``, 2020, online event. Conference Proceedings, 2020, p. 181. Available at: http://www.advancesincleanerproduction.net/9th/files/proceedings_9th.pdf

Chrispim, M. C., Nolasco, M. A., Scholz, M. Oportunidades e desafios da recuperação de fósforo a partir do tratamento de esgoto em países em desenvolvimento (Opportunities and challenges of phosphorus recovery from wastewater treatment in developing countries). In: 2º Seminário Nacional sobre Estações Sustentáveis de Tratamento de Esgoto: recuperação de recursos em ETEs e produção de água para reúso (2nd National Seminar on Sustainable Wastewater Treatment Plants: resource recovery and production of reclaimed water), 2019, Fortaleza. Proceedings. Available at: https://seminarioetessustentaveis.ufc.br/anais/

Chrispim, M. C., Beckinghausen, A. Final Disposal and Valorization of Sewage sludge: a study of current practices and ongoing research. Oral presentation and e-Poster. In: International Summer School and Workshop on "Wastewater and Biosolids Management", 22-27 Jul. 2019. E-book of proceedings, p.26-27. Available at: http://wastewater2019.eap.gr/index.php/e-book-of-proceedings

Chrispim, M.C., Nolasco, M.A., Scholz, M. Resources recovery in wastewater treatment plants in Sao Paulo Macrometropolis. In: 16th IWA Leading Edge Conference on Water and Wastewater Technologies, 10-14 Jun. 2019. Edinburgh, United Kingdom. Online pre-print proceedings, P401.

Chrispim, M. C., Nolasco, M.A. Resources recovery in Wastewater Treatment Plants in large cities. In: 1st Latin American Conference on Sustainable Development of Energy, Water and Environment Systems, 2018, Rio de Janeiro, Brazil.

1. Introduction

This chapter contextualizes the main topic, introduces the research gaps and how this thesis contributes to filling these gaps. Then, the scope and main cross-cutting research questions are presented. Finally, the aim and objectives are presented as well as the structure of the thesis and how the papers are linked to each other.

1.1. Background, research gaps, and motivations

Humanity uses natural resources mainly for the functions of food provision, energy and water supply, as well as for economic growth. However, anthropic activities (e.g., land use, urbanization increase, and population growth) cause impacts on these resources and pose several challenges to cities.

By 2015, the international community, including governments of the United Nations (UN) and other civil society stakeholders, has participated in a process of assessing the progress towards the Sustainable Development Goals (SDGs) and defined a global agenda towards sustainable development. Goals were proposed to be achieved by 2030. Among the established goals are to eradicate hunger and promote sustainable agriculture (SDG 2), ensure access to water and sanitation for all (SDG 6), and ensure access to sustainable energy for all (SDG 7). Regarding SDG 6, a goal related to water and sewage treatment is to expand international cooperation in water and sanitation technologies by 2030, including wastewater treatment and reuse (United Nations, 2015).

Currently, innovative practices and approaches have been discussed on how to integrate the three systems: water, energy, and food production to achieve the sustainable development (Biggs et al., 2015). The integrated approach "water-energy-food nexus" was first conceived and used during the World Economic Forum in 2011 to discuss the strong relationship between the use of natural resources to guarantee access rights to food, water, and energy (World Economic Forum, 2011; Biggs et al., 2015). Later, in 2013, another version of this term appeared, including another component: "Water-energy-land use-food" (World Economic Forum, 2011; Biggs et al., 2015). The integrative approach "Water-energy-food nexus" has become a central part of discussions on how to better understand the connection between these sectors, and how to monitor and achieve the SDGs (Biggs et al., 2015; Rasul, 2016; Wang et al., 2018; Leeuwen et al., 2018). Within this Nexus approach, there are research areas to use natural resources more efficiently, such as innovations to reduce water and energy consumption, and conversion of biomass into fuels and materials (NSF, 2014).

The objectives of wastewater treatment have generally been the removal of carbonaceous organic matter, total suspended solids, chemical pollutants, excess nutrients, and reduction of pathogens before disposing of the effluents in the environment (Verstraete et al., 2009; Tchobanoglous et al., 2015). However, recycling of resources (e.g., nutrients and water) through recovery processes is emerging in sewage treatment systems due to environmental and economic motivations: reducing drinking water consumption and generating revenue for wastewater treatment plants (WWTP) (Mehta et al., 2015; Rao et al., 2017). For instance, urban WWTP are considered crucial systems to enhance phosphorus (P) recycling, and to mitigate eutrophication issues associated with P release from wastewater treatment effluents (Bouzas et al., 2019). So, water utilities (wastewater treatment companies) have a great opportunity to extend their roles beyond the provision of the services (Lam and Van der Hoek, 2020). As they concentrate several resources, they can explore resource recovery to supply raw materials, fertilizers, and/or energy, and consequently benefit from economic opportunities like revenue generation and reduction of operational costs.

Worldwide, sewage sludge management and disposal has become difficult due to the increase in the volume of wastewater treated (Jiménez et al., 2010; Chrispim et al., 2020a), and stringent regulations that make it difficult to apply the sludge to farmland as fertilizer for both disposal and nutrients recycling (Mininni et al., 2015; Chrispim et al., 2020a). Landfilling is a common option for the disposal of sewage sludge mainly in developing countries. However, decreasing land availability, landfill costs rise, as well as increasingly strict legislation and environmental standards will affect the future prominence of landfilling as a disposal technique (Tjandraatmadja et al., 2005; Fytili and Zabaniotou, 2008). From an economic perspective, sludge treatment and disposal represent a high cost in wastewater treatment facilities, about 60% of the total operating costs (Wei et al. 2003). Therefore, it is important to evaluate more efficient and sustainable options, especially considering the increasing in sewage sludge production (Chrispim et al., 2020a).

As an illustration, the quantity of sewage sludge generated in the São Paulo Metropolitan Region (in 2013) was estimated at 890 tons/day (sludge dry basis) considering the five largest WWTP (SABESP, 2013) and it is disposed of in landfills. That is a significant amount that could be used as a resource. The challenge of sludge disposal is also a common reality for other developing countries such as China, where about 40% of the sewage sludge is still improperly disposed of (Lu et al., 2019).

Reducing sewage sludge production and preparing it for further utilization can be considered as cost-effective alternatives in sludge management compared with the standard practice (Chrispim et al., 2020a). The use of sewage sludge as a source of raw materials or energy can produce less resource-intensive consumption patterns (Sfez et al., 2019). In addition, resource recovery from sludge allows for a circular economy and minimizes waste generation and environmental impacts associated with sludge management (Lundin et al., 2000; Mininni et al., 2015). Strategies of valorisation of sewage sludge are addressed in this thesis, including phosphorus recovery, energy recovery, and soil conditioner and organic fertilizer production from composting.

Besides sewage sludge generation, another important impact associated with conventional wastewater treatment systems is energy consumption. Population growth, economic growth, infrastructure expansion, and more stringent legislation on sewage treatment increase the energy consumption in WWTP (Mo and Zhang, 2013). Two complementary aspects can be addressed to achieve energy self-sufficiency in WWTP: energy savings via improving efficiency in unit processes, consequently reducing their energy input, and energy recovery from renewable energy sources in WWTP (Gu et al., 2017). This topic is also analysed in this thesis, particularly the recent developments on energy recovery from anaerobic digestion, and thermal energy recovery from co-processing of sewage sludge.

Based on the technological knowledge developed so far, there is a clear need to adopt a new sanitation paradigm, considering the recovery of renewable resources, such as nutrients, energy, and water from the treated effluent. Several papers in the literature have focused on technologies for resource recovery and their operational conditions, performances, and challenges. However, there are remaining research gaps that should be addressed to facilitate the implementation of resource recovery in WWTP. Van der Hoek et al. (2016) state that the current problem is not the lack of available technologies for resource recovery, but the lack of a planning methodology to identify the most sustainable solutions in each context. Mo and Zhang (2013) argue that few scientific publications have assessed the integration of resource recovery processes at different scales. In this thesis, this gap is addressed especially by the proposal of the framework and its application.

Usually, there is a poor linkage between wastewater treatment sector and agriculture (Van der Kooij et al., 2020). So, there is also a need for studies that consider the linkage of WWTP with local conditions (Fig.1), interactions with the environment and key stakeholders (researchers, policymakers, and end-users) in a holistic approach (Sgroi et al., 2018; Sarvajayakesavalu et al., 2018). Resource recovery depends on specific situations and interacts with several factors (e.g., market, society, legislation, and local economic development). Therefore, identifying legal and institutional challenges related to resource recovery can also contribute to the planning of sewage treatment plants that includes resource recovery strategies. This topic is thoroughly addressed in this thesis, either by the framework application or by the analysis of local conditions in megacities.

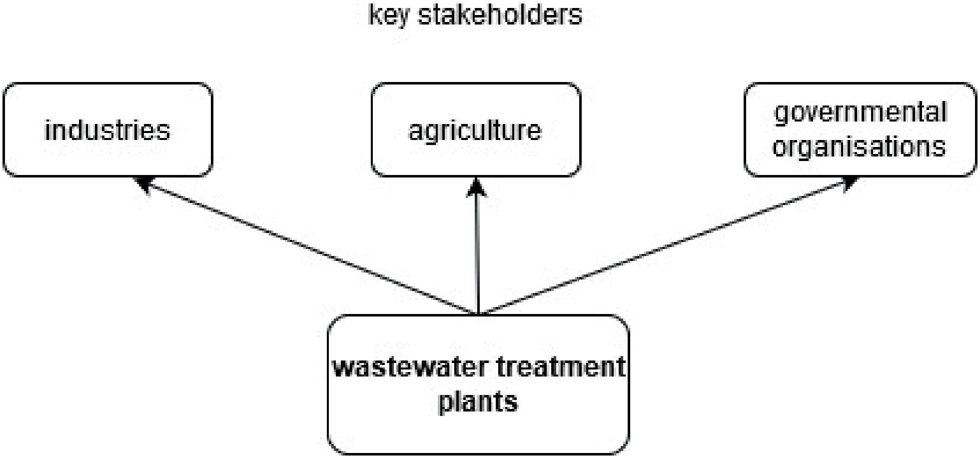

Fig. 1. Connections between wastewater treatment and other sectors and stakeholders.

Currently, how to shift towards a circular economy in wastewater treatment, for example, by integrating resource recovery solutions is a challenging process. The transition towards a circular economy requires a systemic change, and regions play a vital role through the implementation of sustainable strategies (Vanhamäki et al., 2020). Regional studies would provide valuable insights for policymakers by considering local strategies to increase wastewater treatment, for instance through energy recovery subsidies (Breach and Simonovic, 2018). However, regional and large-scale studies on water-energy nexus in urban water systems and research on practical experiences are missing (Vanhamäki et al., 2020). The case studies comprised in this thesis represent an effort to partially bridge this gap at a regional level.

Another research gap within this topic is the lack of reliable, recent, and detailed data regarding wastewater flow rates, treatment performance as well as recovery practices real examples from wastewater treatment works in developing countries (Mateo-Sagasta et al., 2015; Coats and Wilson, 2017). Assessment of applications of water reuse and energy recovery from wastewater treatment plants and monitoring of circular economy application in the water sector are topics rarely explored by studies, especially in developing countries (Guven and Tanik, 2018; Kakwani and Kalbar, 2020). These data and assessments are essential to enable the identification of problems, and evaluation of potentials for improvement, planning and decision-making for resource recovery within urban areas. In a recent systematic review paper (Johannesdottir et al., 2020), the authors have concluded that there is a need for more primary research on technologies for recovery (e.g., carbon or nutrient recovery) and reuse from wastewater especially in Africa, South America, and Asia (apart from China). So, research on this topic can contribute effectively to stimulate actions and resource recovery implementation.

The percentage of the population living in urban areas worldwide is expected to increase to 68% by 2050 (UN Desa, 2018). This urban growth will have effects on the future supply and demand for food, energy, and water (Chang et al., 2020). In this context, sustainable solutions including resource recovery from wastewater are important. The citywide inclusive sanitation approach is based on ensuring access to safely managed sanitation to everyone in a city, promoting a range of solutions while protecting environmental and human health. It includes centralized and decentralized solutions with resource recovery and reuse as well as institutional arrangements, regulations, and well-aligned incentives to promote adequate sanitation systems (World Bank, 2020). The results presented in this thesis, particularly the framework proposed, can support the application of the citywide sanitation approach in centralized systems in urban areas.

Most wastewater treatment plants do not perform recovery practices and are focused only on sewage treatment and disposal to surface waters. Resource recovery is not efficient in the megacities of developing countries. In addition, these regions face similar issues: water scarcity, lack of infrastructure and public services, air, water, land and noise pollution, high population density, lack of provision of clean water and safe disposal of wastewater and stormwater (Khan et al., 2006). In megacities, new challenges arise, because the provision of suitable sanitation is expensive and requires infrastructure expansion through the building of sewer networks and increase of treatment plants capacity (Tjandraatmadja et al., 2005). Considering their characteristics, megacities have larger impacts on water resources than smaller cities or rural settlements. In this context, the conservation of water resources should be a priority for all megacities. Appropriate treatment and reuse of municipal wastewater for non-potable uses is a cost-effective water conservation measure. Additionally, the introduction of innovative and affordable resource recovery solutions in such cities could improve wastewater infrastructure and provide many environmental, social, and economic benefits.

1.2. Scope

This research considers municipal wastewater treatment as a source of renewable resources. This thesis includes two case studies in the Macrometropolis of Sao Paulo, the most populous area in Brazil (Papers II and III) and addresses other similar megacities in developing countries (Papers II, III, and IV). In Brazil, there is a shortage of research on the implementation of resource recovery actions for different locations, and little progress has been made in data collection to support the development of coherent policies for resource recovery (Chrispim et al., 2020b). Thus, it is necessary to expand the scientific knowledge in order to contribute to a new vision about wastewater treatment in the cities, besides analysing technologies and processes that can be feasible according to technical, economic, social, and environmental aspects. The data gathered and analysed in this thesis can provide guidance in this subject and support sustainable decisions at WWTP and regional levels.

The present study includes the analyses of the current situation of existing WWTPs regarding resource recovery implementation in some megacities in developing countries, in detail for the Macrometropolis of Sao Paulo. A second case study addressed a representative WWTP to test a proposed framework and simultaneously identify opportunities, including processes and technologies for resource recovery.

Although global literature in the field was consulted in all the four papers (e.g., in the discussions of the results and the review papers), this research focused particularly on metropolitan areas of developing countries. Therefore, the results can help the elaboration of resource recovery projects in wastewater treatment mainly in the study area and provide guidance for planning of configurations that allow the improvement of the WWTPs, making them more sustainable. In a broader context, the results could also contribute to the creation of technical and scientific knowledge and a better understanding of planning, retrofitting, and upgrade of municipal WWTP with resource recovery, and to support the creation of public policies and regional programs in this field.

1.3. Aim and objectives

This thesis presents a comprehensive knowledge base for wastewater treatment plant managers, operators, and decision-makers to a better understanding of resource recovery solutions and actions needed to facilitate the transition towards sustainable sanitation systems.

Aim

To guide planning, technology and policy development towards resource recovery from wastewater treatment plants in large cities of developing countries.

Specific Objectives:

i. to characterize quantitatively and qualitatively the flows (water, phosphorus, organic matter, and by-products) and the potentials for resource recovery in a representative WWTP case study

ii. to recommend operational and technological strategies for resource recovery (phosphorus and energy) to be applied in this representative facility, considering economic, technical, environmental, societal, and political indicators

iii. to characterize and map the current situation of existing WWTPs in the Macrometropolis of Sao Paulo and compare it with other representative metropolitan areas (in developing countries), regarding implementation of resource recovery strategies in their wastewater treatment systems

iv. to identify relevant factors that can encourage or hinder (barriers) the implementation of resource recovery from municipal wastewater treatment

v. to provide a generic framework to support and facilitate planning and decision-making towards the implementation of resource recovery strategies in large cities

vi. to identify suitable technologies that could be applied in the studied megacities, after examining technologies that are being used in wastewater treatment plants to recover phosphorus and energy

vii. to analyse recent technological advances related to biogas production and how local factors may affect the implementation of energy recovery in megacities of developing countries.

1.4. Thesis structure, connections among the papers, and research questions

This thesis follows the format of a compilation of papers introduced in the present thesis summary. A brief description of the appended papers and their interconnections are presented in the following paragraphs and in Figures 2 and 3.

The papers address the objectives as follows.

Paper I: (iv) and (vi)

Paper II: (iii), (iv), and (v)

Paper III: (i), (ii), (v), and (vi) for the Sao Paulo region.

Paper IV: (iv), (vi) and (vii)

In **Paper I**, the main barriers related to resource recovery implementation were identified, besides a comparison of the main technologies (for phosphorus recovery) and the potential of implementation of nutrient recovery in developing countries, particularly in the Latin America and Caribbean region, is explored.

The case study (**Paper II**) includes an analysis of the current situation in some megacities, mainly in the Sao Paulo region (the most populous in South America), the main barriers and opportunities for improvement and scaling up resource recovery measures. Also, Paper II introduces a new framework tool proposed by the authors to support planning and decision-making.

This thesis comprises another case study (**Paper III**) but at a smaller scale, considering a representative WWTP in São Paulo Megacity to illustrate the proposed framework application. The application was based on the case study-specific data and information from the current literature. The results include an assessment of resource recovery scenarios for the studied region, quantification of resource recovery potentials, and framework improvement suggestions that can guide potential applications in other contexts.

Finally, **Paper IV** addresses energy recovery in detail. Two recent and relevant topics within biogas for energy recovery field: technological advances and local conditions for implementation are addressed. Techniques for enhancement of biogas production such as co-digestion and microalgae growth were reviewed, and research gaps were identified. The paper also discusses how local conditions affect energy recovery implementation in three megacities (Sao Paulo, Mexico City, and Cairo). This paper contributes to establishing future directions for the research field on energy recovery from wastewater, particularly related to biogas.

Figure 2 highlights the linkages among the papers (except between Papers I and IV).

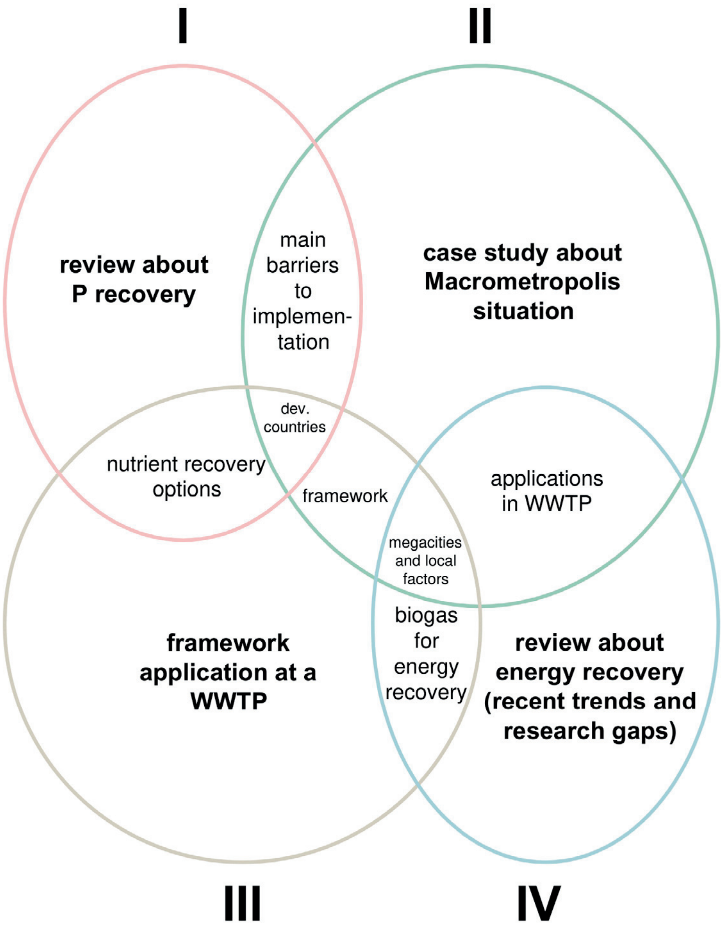

Fig. 2. Interconnections between the papers. Dev.= developing.

All the papers are interconnected as shown in Fig. 3. In Papers II, III, and IV we considered some of the barriers identified in Paper I and analysed them in more detail. For instance, in Paper II a tool was proposed to support planning and decision-making. Paper III is linked to Paper I because while Paper I highlights the need for studies that assess environmental impacts of resource recovery technologies, Paper III provides this assessment for the four proposed recovery scenarios. Paper III is also related to Paper II since it illustrates the framework application. Paper IV relates to Paper I. For example, in Paper I conclusions it is suggested to further analyse the effects of regulations as drivers or barriers to implementation of resource recovery in WWTP. Then, this is explored in Paper IV for energy recovery. Non-technological barriers as well as technological research gaps are explored in the papers (for phosphorus recovery in Paper I, and energy recovery in Paper IV).

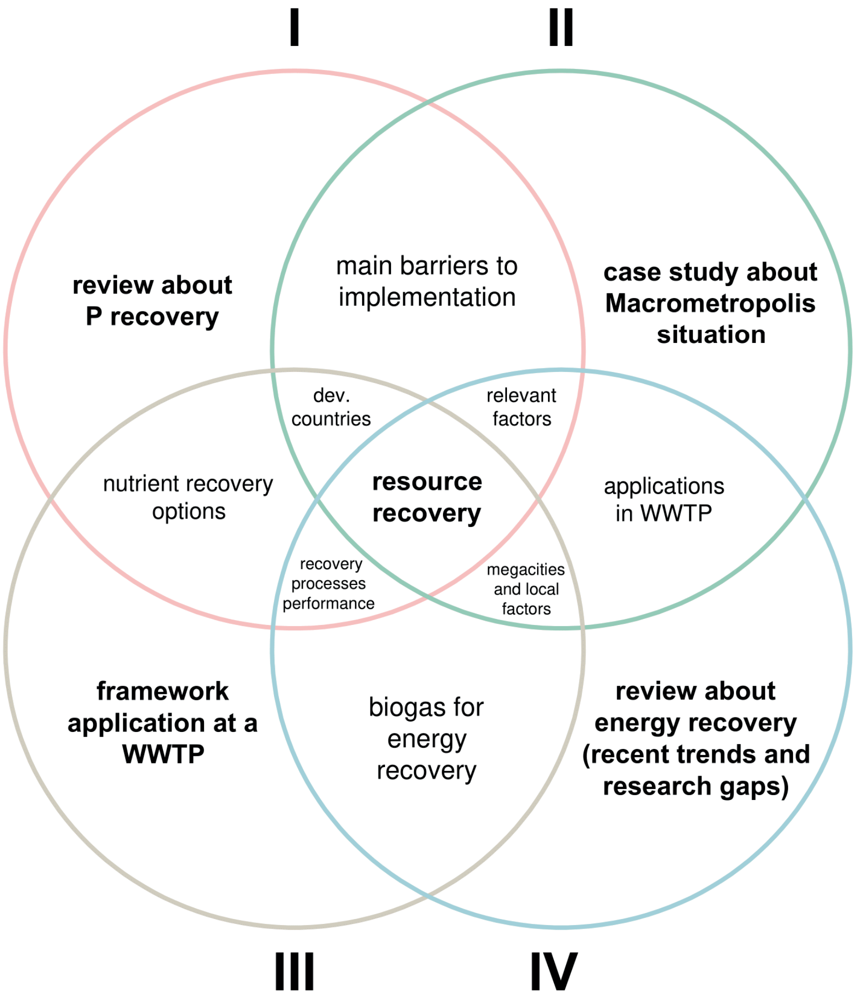

Fig. 3. Linkages among the four papers. Dev = developing.

In all the papers, there is a particular reference to developing countries' context. However, in general, the information and knowledge presented in this thesis could be useful for governments, stakeholders, and researchers to develop resource recovery, for other urban areas beyond the assessed megacities.

Our findings may guide further technological development, decision-making on this topic, and support transitions to sustainable and efficient WWTP, mainly in developing countries. In all the papers the reasons why resource recovery is still little implemented in wastewater treatment plants (particularly in developing countries) are explored. All the papers were developed with the purpose of contributing to answer the main question: How to integrate wastewater treatment with resource recovery practices?

The main research questions and cross-cutting themes addressed are:

What resources are present in municipal wastewater?

What resources can be recovered and in what treatment processes? Is it possible to recover resources at different scales?

In what contexts is resource recovery from wastewater treatment important? Why? What are the driving forces behind this transition?

What are the main technologies currently used in the world to recover phosphorus from municipal wastewater?

What are the recent advances to enhance biogas production for energy recovery?

How to recover resources in wastewater treatment processes in a specific context (such as the case of the Macrometropolis of São Paulo)?

What are the barriers related to the implementation of resource recovery schemes at WWTP in the Macrometropolis of São Paulo?

What is the local demand for resources and who are the key stakeholders in this region?

How local factors (e.g., legislation, existing infrastructure, public acceptance) interfere with the deployment of resource recovery strategies (whether to encourage or restrict)? Is there an enabling environment for resource recovery in the São Paulo region and other megacities?

This first section (Introduction) aimed to present mainly the motivation and research objectives of this thesis. The remainder of the summary is structured as follows. Chapter Two provides a brief explanation of the research design, the methods used, and the limitations. In Chapter Three, the main results from the appended papers are summarised and briefly discussed. Finally, Chapter Four presents the main conclusions and recommendations for future work.

2. Methods

This chapter provides a brief description of the research design, including data collection and analysis steps. For further details, the reader is referred to the appended papers. The chapter closes by presenting the limitations and ethical considerations.

2.1. Data collection and the studied regions

The case study approach (Yin, 2009) and literature reviews (Torraco, 2016) were the main methodologies used to achieve the thesis objectives. Both generic and context-specific data were collected. Figure 4 summarises the main methods for the data collection in all the four appended papers.

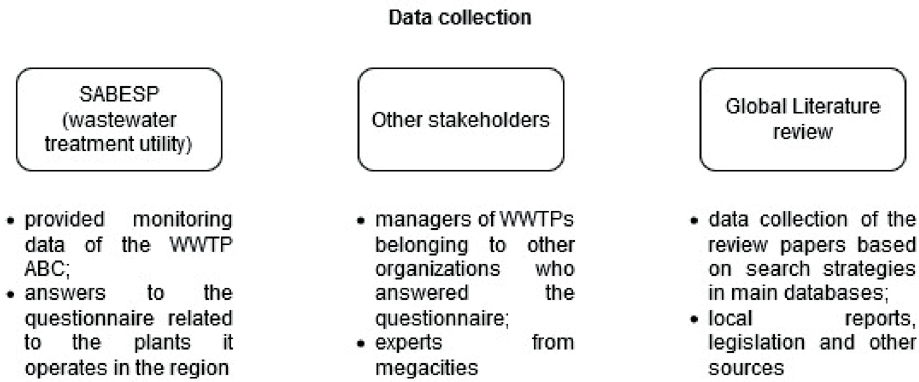

Fig.4. Illustration of the ways of collecting data for this thesis.

Quantitative and qualitative data were obtained from several sources. SABESP (wastewater treatment utility) provided data related to a part of the plants in the study region (including the detailed data of WWTP ABC- the case study in Paper III), and the list of contacts of managers in each metropolitan region who answered the questionnaire. Other organisations such as wastewater treatment utilities, private companies, and city councils in the study area also responded to the questionnaire.

EMPLASA (Sao Paulo Metropolitan Planning Company S/A) provided updated data about the Macrometropolis of Sao Paulo (e.g., population, gross domestic product, among others). For the review papers, several search strategies in the main databases were conducted.

2.1.1. Case studies (Papers II and III)

This thesis includes two case studies. The first (Paper II) was carried out to understand the local context of wastewater treatment and resource recovery situation in a large urban region. The second case study (Paper III) comprised a smaller scale (one WWTP and the surrounding municipalities), with the purpose to apply the framework to testing it and recommending resource recovery solutions appropriate for a specific context.

In Paper II the study region was the Macrometropolis of Sao Paulo (Fig.5), the most populous urban agglomeration in the Southern Hemisphere. This region accounts for 50% of the urbanized area of the State of São Paulo, concentrating about 75% of the state population and including 174 municipalities, including Campinas, Santos, São José dos Campos, Piracicaba, and Sorocaba (EMPLASA, 2019). The Macrometropolis of Sao Paulo comprises 5 metropolitan regions and 3 urban agglomerations (Fig.5). One of its metropolitan regions is the Metropolitan Region of Sao Paulo or Sao Paulo megacity, which was also the study area for Paper III. This metropolitan region concentrates more than 10% of the inhabitants of Brazil in less than 0.1% of the territory of the country (Ribeiro, 2011; Senese Neto; 2018). The Macrometropolis presents high importance for the economy at both State and national levels.

This region faces several challenges in water and sanitation, for example, water scarcity, rivers heavily polluted by the discharge of untreated sewage, and conflicts over different uses of water. The water availability per capita per year in the Metropolitan Region of Sao Paulo is 143 m^3, which is considered a situation of absolute water scarcity by the United Nations (below 500 m^3 per capita per year) (United Nations, 2014a; Soriano et al., 2016; Cardoso, 2019).

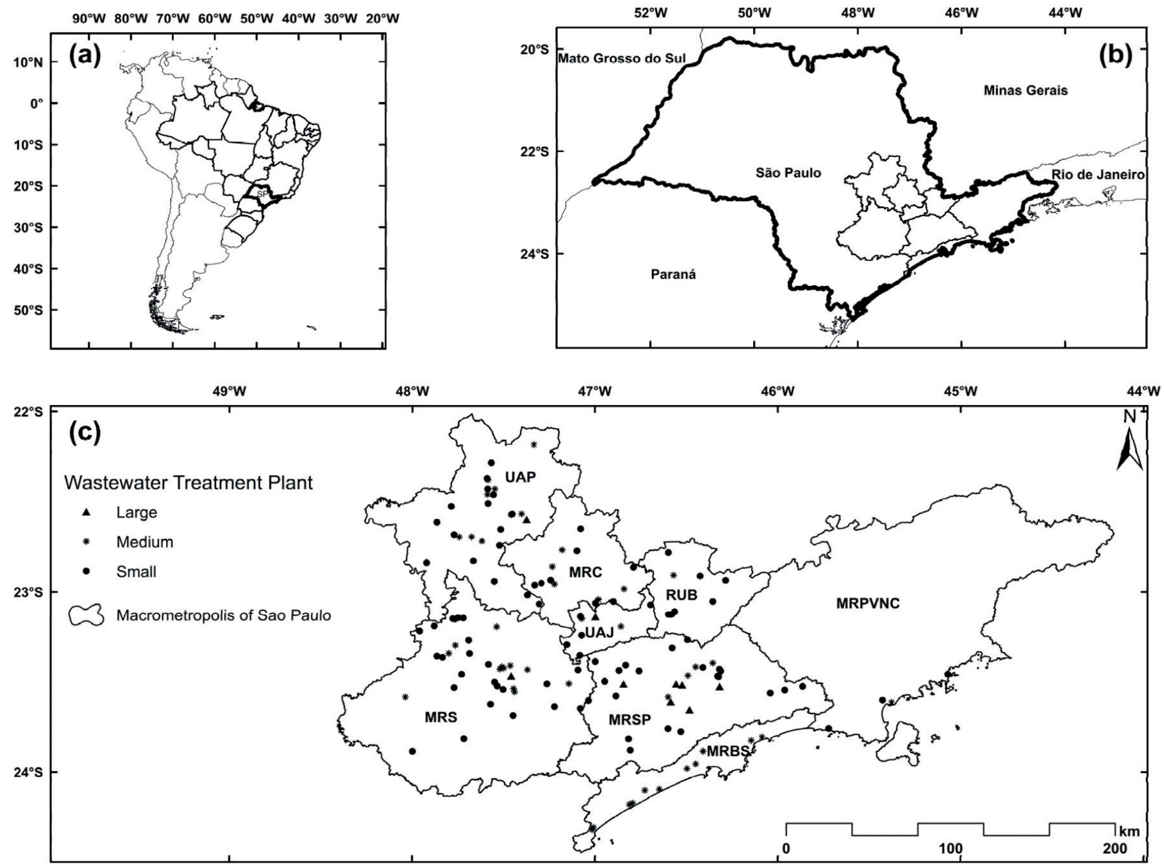

Fig. 5. Map of the study area of Paper II- the Macrometropolis of Sao Paulo, Brazil. RUB, Regional Unit Bragantina; UAJ, Urban Agglomeration of Jundiaí; UAP, Urban Agglomeration of Piracicaba; MRBS, Metropolitan Region of Baixada Santista; MRC, Metropolitan Region of Campinas; MRS, Metropolitan Region of Sorocaba; MRSP, Metropolitan Region of Sao Paulo; MRPVNC, Metropolitan Region of the Paraíba Valley and the North Coast. Source: Chrispim et al., (2020b).

There is a current Contingency Plan for the Water Supply for the Metropolitan Region of Sao Paulo that includes several actions, such as: to complement and replace potable water by alternative sources for non-potable purposes, and to reduce water losses in the distribution systems and irregular abstractions (Water Crisis Committee, 2015). The Macrometropolis of São Paulo is considered the new space unit of reference for water management in the State of São Paulo (Pires do Rio et al., 2016). The ´´Sao Paulo Macrometropolis Water Resources Utilization Plan`` proposes new abstractions of water from other sources that are distant and of interest to other regions (Tagnin et al., 2016). Therefore, the evaluation of resource recovery strategies, especially water reuse, is important to support the decision-making on projects in this area. According to projections, for the coming years, there is a trend of increasing water demand and population in the Upper Tietê river basin (DAEE, 2013; FABHAT, 2015). There is also a projection that the demand for water in the Macrometropolis of Sao Paulo will be 283.07 m^3/s (considering urban supply, irrigation, and industrial use) in 2035 (Government of the State of São Paulo et al., 2013; Pires do Rio et al., 2016).

Considering the characteristics of water vulnerability, the high population concentration, socio-economic urbanization features, the great consumption rate of natural resources, and the climate zone, the region of Sao Paulo was chosen as a representative case study for other megacities in developing countries.

First, the organizations responsible for the WWTPs in each municipality belonging to the Sao Paulo Macrometropolis were identified. Then, to collecting the data of WWTP in the Macrometropolis, a questionnaire was elaborated (based on Papa et al., 2017) and forwarded to the managers of all wastewater treatment companies in the study area. This method was chosen since the required data were not available in other sources (e.g., websites, publications, or reports). For more information about the questionnaire please consider Supplementary Material (SM) 1 and Figure 2 of Paper II.

Additional data were collected to enrich the discussion, such as the sewage collection and treatment rates in each municipality, and the number of WWTP in each municipality. These data were obtained from the sources: Sewers Atlas: Reducing pollution of River Basins from the National Water Resources Information System (SNIRH), which contains information about the number of plants for each Brazilian city and other related data (SNIRH, 2013); the Information System on Sanitation for Sao Paulo State (SISAN, 2016); and Water and Sewage Services Diagnostics of the National Sanitation Information System (SNIS, 2018; SNIS 2019a, 2019b). Based on the results of the Macrometropolis survey, a framework was created to support planning and decision-making.

In Paper III, the data were collected to apply the framework in a large WWTP in Sao Paulo city (Fig. 6). Data related to the plant (i.e., regularly recorded measurements) were collected from the responsible company (SABESP). The list with the required data (general data, characteristics of the treatment processes, monitoring data, by-products, and environmental indicators) to the plant is available in Supplementary Material 1 of Paper III. Complete description of the studied facility (WWTP ABC) treatment processes and additional information are in Supplementary Material 2 of Paper III.

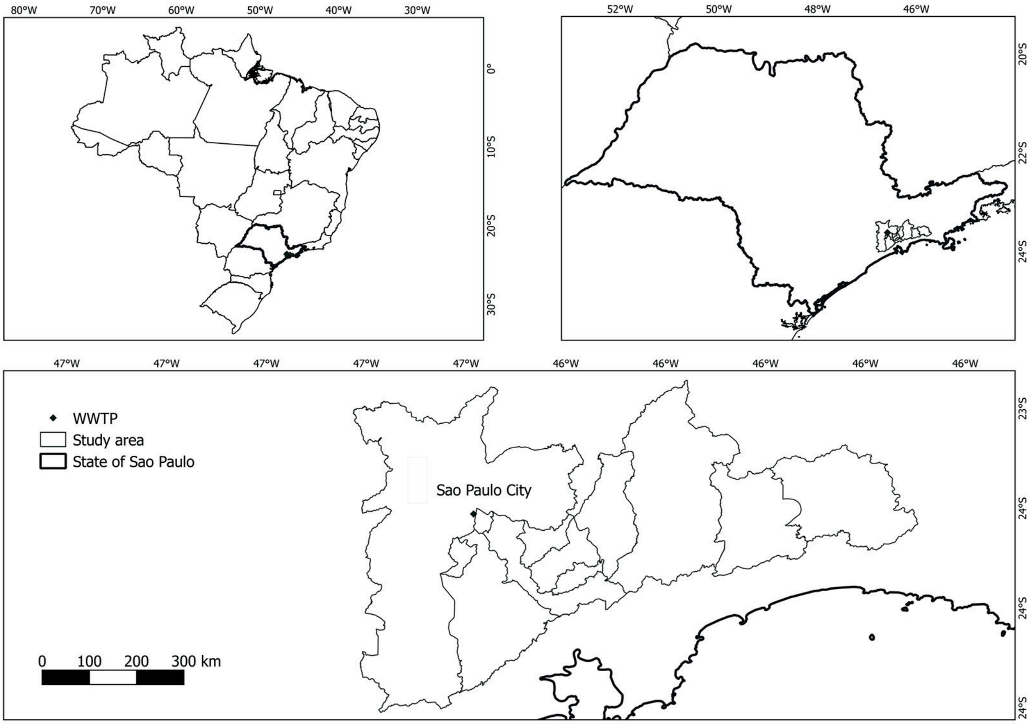

Fig.6. Map of the study area in Paper III (e.g., Steps 2 and 4), including the location of the WWTP in the Sao Paulo megacity. Source: Chrispim et al. (2020c).

The temporal boundary of the analysis comprised a period of one year (from 2016/07/01 to 2017/06/30), so the monitoring data refer to this period. The definition of this period followed the recommendation of Brunner and Rechberger (2004). To achieve the other steps of the framework, data were collected from various sources, through consulting the related legislation on water reuse, sludge recycling, and energy recovery, technical reports, regional databases, journal articles, and planning documents for the study area. Scenario analysis was used to explore some possible resource recovery measures for the studied plant. Detailed information for each attribute/indicator can be found in the Supplementary Materials 3 and 4 of Paper III.

Besides São Paulo megacity, other megacities were analysed in Papers II, III, and IV. Most of the world megacities today are in developing countries (United Nations, 2014b; United Nations, 2018; Aggarwal and Haglund, 2019; City Population, 2020). Figure 7 presents the most populous cities in the world. Many metropolitan areas in developing countries have been facing water scarcity and water-related issues, especially because of rapid urban growth (Britto et al., 2019). For instance, these megacities share common issues such as the growth of informal settlements in protected areas (e.g., occupations in the surroundings of surface waters), and qualitative commitment of surface waters (Aggarwal and Haglund, 2019).

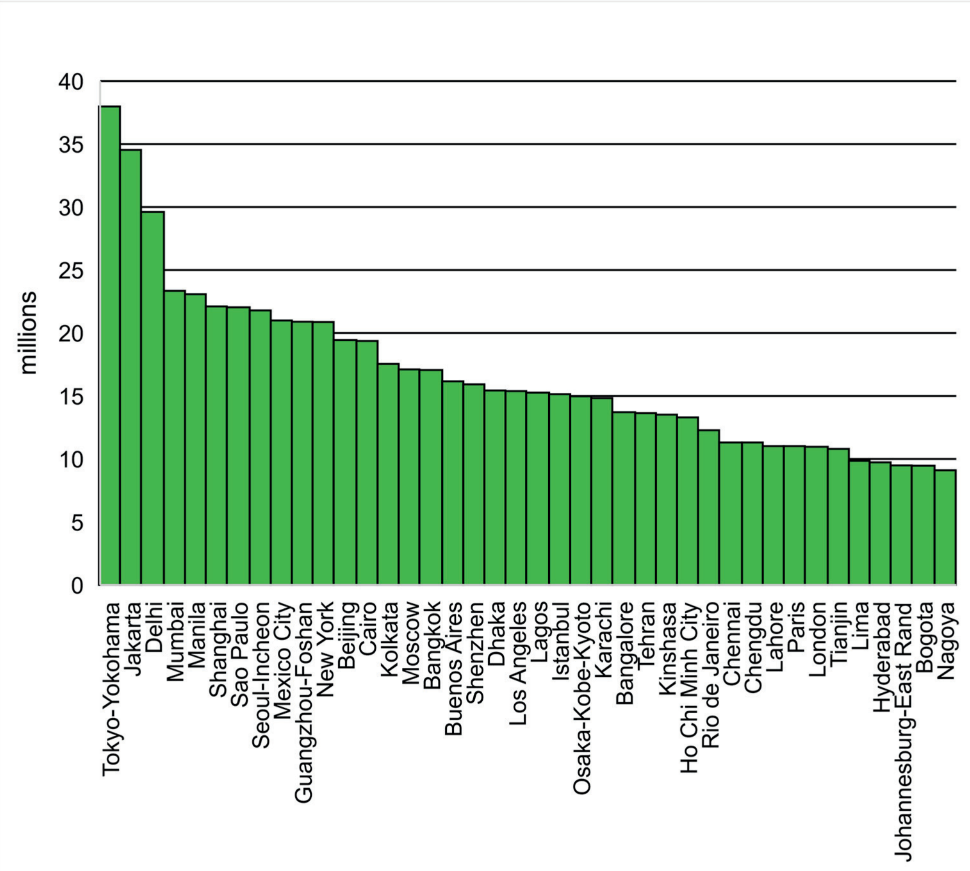

Fig. 7. Most populous megacities in the world. Data refer to the year 2020, based on Demographia (2020).

In Paper II, some cities (Moscow, Johannesburg, and Shanghai) of BRICS (Brazil, Russia, India, China, and South Africa) countries were briefly compared in the discussion. The data from these megacities were obtained from the literature. In Paper III, more specific data were collected to make indications on the potential of framework applicability in seven megacities (Mexico City, Johannesburg, Cairo, Chengdu, Shanghai, Delhi, and New York). This evaluation was based on expert's judgement of the authors (after consulting with local experts in the area, local reports, urban sustainability indexes, and literature).

All the selected megacities have approximately 10 million inhabitants or more, based on the most updated data sources: Demographia (2020) and City Population (2020).

2.1.2. Critical literature reviews (Papers I and IV)

To investigate the main phosphorus recovery processes worldwide a systematic literature review was done in Paper I by consulting several databases: Scopus, Web of Science, Aquaculture Compendium, Emerald Insight, and the websites: Integrated Search Portal (SIBI/USP), Scielo, and Science Direct. The literature review was also important to identify the main barriers and opportunities concerning resource recovery. The used keywords and expressions are given in the Methods section of Paper I. Additional searches focused on developing countries were performed. Other sources (grey literature publications) were consulted to obtain important information that did not show up in the journal papers, such as the websites of the companies that developed phosphorus recovery technologies and reports by the United Nations.

For Paper IV, a systematic literature review was conducted, using the databases Web of Science Core Collection and Scopus, by filtering the time to the range of the year 2015 to November of 2020. The selection of papers was based on their content. All the used keywords and procedures are described in the Methods section of the paper. Grey literature sources such as technical guidance documents about biogas and energy recovery (e.g., The International Energy Agency) were consulted to complement some information. The analysis of how local conditions affect the implementation was limited to three megacities- Sao Paulo, Mexico City, and Cairo. Besides consulting the relevant literature, the authors consulted with local experts (from Brazil, Mexico, and Egypt) and accessed local reports sent by them to gather more specific data to complement the analysis.

2.1.3. Summary of the main methodological aspects

Table 1 summarises the key information regarding the data collection for the four appended papers and the research objectives.

Table 1. Synthesis of the methodological aspects of this research

Specific Objective	Collected data	Methods of Data collection	Research Output(s)
To characterize quantitatively and qualitatively the flows and potentials for resource recovery in the operational units of a representative WWTP case study	Monitoring data of the plant (e.g., physico-chemical parameters, by-products generation, environmental indicators)	Case study. List of requested data was sent to the responsible organisation; visit to the plant; content analysis of reports; quantification of mass flows and concentrations; and calculation of removal efficiencies	Paper III
To recommend operational and technological strategies of resource recovery to be applied in this representative facility, considering sustainability indicators	Based on the dataset (i.e., results of characterization from the previous objective), local demand and legislations analysis; secondary literature related to water, energy and socioeconomic data of the surrounding area (e.g. water consumption in industries and etc.). Other input data were collected to apply the framework	Case study. Literature review on resource recovery technologies; framework application including demand mapping (based on regional databases, journal articles, and planning documents analysis), stakeholder analysis, institutional analysis	Paper III
To describe and map the current situation of the Macrometropolis of Sao Paulo and other representative metropolitan areas (in developing countries), regarding to implementation of resource recovery strategies from wastewater treatment	Responses to the questionnaires (e.g. initiative of resource recovery, interest or future plans and details) from the WWTP managers; data about water reuse, nutrient recovery and energy recovery implementation and key elements (recovered volume, final product, and etc.)	Case study. Survey using questionnaires to collect data from all the WWTP in the study area; local documents and databases consultation (e.g., National Sanitation Information System); literature review to getting data of other metropolitan regions in developing countries	Paper II
To identify relevant factors that can encourage or hinder (barriers) the implementation of resource recovery from municipal wastewater treatment	Secondary literature- papers including technical, social, economic, political, and institutional aspects related to resource recovery; responses to some questions (questionnaire)	Literature review in the main research databases; institutional and policy analysis (e.g., legislations); and responses from the survey with the managers (Paper II)	Papers I, II and IV
To provide a generic framework to support and facilitate the transition to wastewater treatment plants with resource recovery strategies in large cities.	Results from Papers I and II; literature in the field of planning for resource recovery	Personal experience, based on the previous papers (I and II), and literature review to set the indicators	Papers II and III
To identify suitable technologies that could be applied in the studied megacities to recover phosphorus and energy	Secondary literature- selected papers which contained information about phosphorus and energy recovery processes; factors that affect implementation (from Papers I, II, and III).	Literature review in the main research databases; comparison with the local conditions in megacities; and framework application	Papers I, III and IV
To analyse recent technological advances related to biogas production and how local factors may affect implementation of energy recovery in megacities of developing countries	Secondary data from papers about technologies for enhancement of biogas production; local conditions data for each megacity; literature about WWTP cases with biogas recovery	Literature review; document analysis (e.g., local reports) to check the existence of benefits and incentives to biogas recovery	Paper IV

2.2. Data analyses

In Paper II, the content of the data collected by the questionnaires was analysed and organised into Excel spreadsheets for comparison and further analyses. Data of all the WWTP were analysed from some parameters such as the size of the plant, wastewater inflow rate, treatment of liquid and solid phases, location (e.g., which metropolitan region belong; rural or urban municipality), and according to each question of the questionnaire. The results were represented as figures (e.g., maps, diagrams, and graphs) and tables. Key factors that affect implementation were mapped, priority areas for resource recovery (e.g., water reuse) were identified, and suggestions for improvements were given. Finally, a framework was created based on the results of the survey. The suggested set of indicators (in step 9) were based on previous literature (Van Der Hoek et al., 2016; Hu et al., 2016; Sikosana et al., 2017; Harris-Lovett et al., 2018; Woltersdorf et al., 2018).

Paper III was mainly based on the collected raw data about the representative plant and the study area. Mean concentrations, organic and nutrient loads, and removal efficiencies for the main parameters (COD, BOD, N, and P) were calculated. Then, the main results were represented as tables and figures. The final step was a comparison between the recovery options according to the indicators. The outlook (recovery scenarios) was a result of the different assessment indicators given in this work (educated guesses) and based on the literature and the WWTP data. Further explanation about the resource recovery scenarios is in Supplementary materials 3 and 4 of Paper III.

In Paper I, the recovery technologies were grouped by each phase (liquid or solid, and the latter was subdivided into sewage sludge and ashes). Overview tables were created to assist in the identification of the main challenges and opportunities for resource recovery implementation, classifying them into social, economic, technical, and political/institutional challenges.

In Paper IV, based on the results from the searches in bibliographic databases, the selection of the papers was performed using Bibliometrix tool (Aria and Cuccurullo, 2017) RStudio and Excel spreadsheet with Ordination classification as reported by Baldam (2020). Then, the selected papers were grouped based on each topic of the article (e.g., co-digestion, microalgae, megacities data, and so on). Data were represented in figures and tables, and the main research gaps in the field of enhancement of biogas production, particularly microalgae growth, co-digestion, and thermal pretreatment were identified by the authors. The choice of the local factors was based on Diaz-Elsayed et al. (2020), Chrispim et al. (2020b), and Chrispim et al. (2019). This assessment was made considering the data available in the reviewed publications.

2.3. Limitations

The findings of the case studies (Papers II and III) represent the situation in the monitored period, but the study region is dynamic, so the analyses should be updated in the future. Some wastewater treatment organizations did not answer the questionnaire, which limits the interpretation of the findings (in the survey of Paper II). Other limitations were difficulty with the estimation of costs of recovery technologies (in scenario analysis of Paper III) due to no real application in the area; and lack of some data (e.g., monitoring of sewage sludge quality parameters in the studied WWTP in Paper III).

Regarding the non-responsive plants limitation of Paper II, it does not seem to significantly affect the results because the metropolitan region with the lowest responses (MRPVNC) corresponds to only 8% of the total flow of the treated wastewater in the whole Macrometropolis region. MRPVNC includes the North Coast and the Paraíba Valley subregions. The largest plants of the North Coast were included in the survey; however, we did not get responses from the largest plants of the Paraíba Valley area. Also, there are many municipalities without WWTP in this metropolitan region, and it corresponds to the second-highest flow of untreated and not collected sewage when compared to other metropolitan regions of the Macrometropolis.

2.4. Ethical considerations

In the part of the research (Paper II) which involved the managers' participation, the questionnaires were sent by e-mail with an informed consent form to educating the participants about the purpose of the research and to guaranteeing the participants the respect for their rights, following ethical standards. In this consent form, they were given a brief introduction about the project, their role, and how the information obtained from the questionnaire would be used in the research. Also, the participants were informed that their names would not be used in any publication unless their permission was sought, and a summarised report was provided to them for approval. These procedures were also followed for Paper III research when some data were collected with a WWTP company.

The publication resultant from the survey which was based on the managers' responses (Paper II) was shared with all the participants- responsive managers of WWTP. Paper III was shared with the wastewater utility responsible for the WWTP ABC. Also, a workshop is planned to occur online soon in which the essence of the findings of both papers will be presented to all the participants.

3. Results

In this section, the main results of the appended papers are presented and are briefly discussed within a wider context. This chapter closes by presenting the communication of the results and expected impacts to the Sustainable Development Goals.

3.1. Phosphorus recovery review (Paper I)

This section was divided into two based on the main contents of Paper I. Firstly, a general contextualization about resource recovery and after specifically for phosphorus review results.

3.1.1. Contextualization about the resource-oriented sanitation approach

The "Resource-Oriented Sanitation" approach focuses on the recovery of resources, prioritizing water reuse, energy recovery, and recycling of sewage constituents (nitrogen, phosphorus, organic matter, among others) to generating added value products (Morandi et al., 2018).

Many resources can be recovered from wastewater, such as reclaimed water for potable and non-potable purposes; nutrients as fertilizers and soil conditioner; bioenergy and biofuels (Solé-Bundó et al., 2019); proteins for animal feed or human feed supplements (Capson-Tojo et al., 2020); alginate; cellulose; polyhydroxyalkanoate (for bioplastic production) (Valentino et al., 2017; Leeuwen et al., 2018); ashes (from incinerated sludge) as raw material for concrete, cement, and bricks manufacturing (Raheem et al., 2018); grit (Papa et al., 2017); rare earth elements (e.g., gadolinium), metals (copper, zinc) (Puyol et al., 2017; Jadhav et al., 2017; Kegl et al., 2020) as well as enzymes (e.g., protease, catalase) for industrial applications (Gherghel et al., 2019). Some of these resources such as proteins and enzymes are recovered by emerging technologies that are not yet applied at full-scale and require further research and development as well as reduction of costs. Table 2 presents some examples of resource recovery pathways in wastewater treatment. Some of them (e.g., anaerobic digestion, co-processing, microalgae systems, struvite precipitation, and water reuse) are addressed in this thesis through the appended papers. In Paper I, P recovery processes were analysed.

Table 2: Synthesis of the main processes and applications for water reuse, energy, and nutrient recovery

Type of resource recovery	Processes	Potential applications
Energy recovery	Anaerobic Digestion Co-processing of biosolids Gasification Pyrolysis Small hydropower plants with effluents Heat pumps Bioelectrochemical Systems Microalgae growth	Electricity generation, heat recovery, and biofuel production
Nutrient recovery	Struvite precipitation Biomass growth (e.g. microalgae) Ion exchange Phosphorus recovery from sewage sludge and ashes Biosolids after anaerobic digestion	Application of biosolids in soil (soil conditioner), use of fertiliser in agriculture for different crops, for restauration of degraded lands, and for landscaping
Water reuse	Tertiary treatment (e.g., membrane bioreactor, reverse osmosis) Secondary treatment followed by disinfection (depending on the treated effluent quality and final application)	Irrigation in agriculture Industrial reuse Urban reuse Direct potable reuse Indirect potable reuse Recharge of aquifers

Source: Modified from Cornejo (2015).

3.1.2. Performance of phosphorus recovery processes, challenges, and opportunities for developing countries

This paper aimed to guide phosphorus recovery options in wastewater treatment sector. The focus was particularly on developing countries such as the region of Latin American and the Caribbean. Methods for phosphorus recovery at full-scale, pilot-scale, and laboratory-scale are presented and compared (e.g., in terms of recovery rate, scale, and recovered product). Then, the environmental impacts and benefits associated with phosphorus recovery strategies are discussed. Figures 8 and 9 summarise the main topics addressed in this paper.

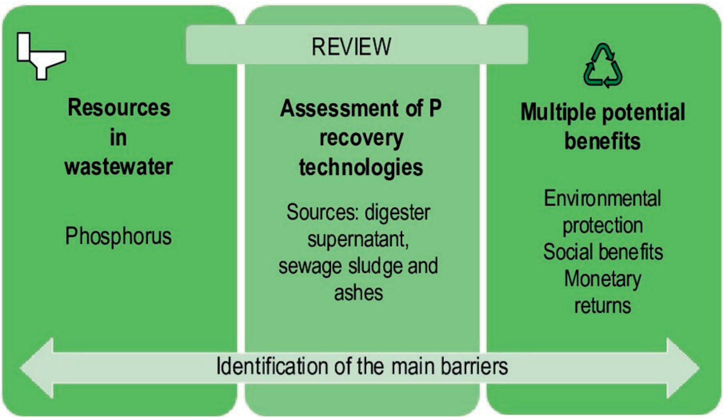

Fig. 8. Summary of the main content of Paper I. Source: Chrispim et al. (2019).

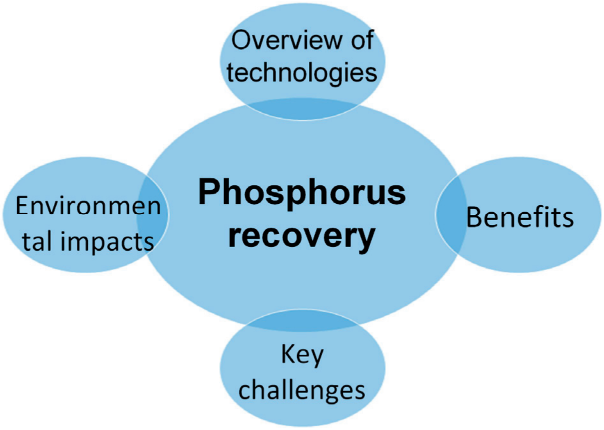

Fig. 9. Topics addressed in Paper I.

The major drivers for resource recovery strategies are the value and the limited availability of fertilizers (mainly phosphorus), growing energy costs, stricter regulations on nutrient removal for effluent discharge, and reduction of maintenance costs of wastewater treatment works (Batstone et al., 2015; Chrispim et al., 2019). The incorporation of resource recovery strategies into WWTP becomes their processes more efficient and reduces the amount of waste (environmental and economic benefits). The use of alternative water sources and recovery of nutrients from sewage contribute to sustainability in the agriculture and sanitation sectors.

Phosphorus is a finite resource and an essential nutrient. Phosphorus limitation for plant production is a worldwide issue (Hou et al., 2020). The main benefits of phosphorus recovery are the generation of an alternative and renewable source of fertilizer, reduction of costs associated with sludge management (transport and final disposal), prevention of eutrophication of water bodies due to lower phosphorus concentrations in the final effluent discharged to surface waters, avoidance of operational problems related to struvite precipitation in pipes and equipment, and potential to contribute for increasing food security.

The most common method for phosphorus recovery is the chemical precipitation of struvite, especially for secondary streams (sludge line), which have higher P concentrations. Other recovery processes have been studied such as ion exchange with zeolites; biomass production (e.g., microalgae growth); and vivianite recovery from digested sludge. But these processes require further development to reach commercial applications.

The comparison of processes from liquid and solid phases (Tables 1-3 of Paper I) shows that the recovery rate of P (in % of the WWTP influent) from liquid phase may reach 10-60% while the recovery rate from sludge is in the range of 35-70% and from ashes 70-85%. The main products are struvite, calcium phosphate, iron phosphate, and phosphoric acid. Some processes based on sewage sludge ashes also enable recovery of aluminum and iron coagulants.

The main environmental concerns related to recovery processes are energy consumption, reactants demand, and heavy metals contamination. Recovery processes from liquid-phase generate fewer emissions and have lower energy demands, but lower recovery rates than solid-phase processes. For recovery from ashes, there is a concern related to heavy metals decontamination. Based on the consulted publications, several phosphorus recovery processes present high removal of heavy metals (98%), indicating no concerns for pharmaceuticals and heavy metals in struvite products as they meet the European Union legal limits (Egle et al., 2016; Vlaeminck et al., 2020).

For countries where sludge incineration is not a common practice (no existing mono-incineration facilities) or for small scale treatment plants, phosphorus recovery from ashes is not a suitable alternative. In developing countries, the solutions for phosphorus recovery should have low costs, high recovery rates, no specialized labour requirement for operation and maintenance, and no large space need. In the Latin American and the Caribbean, the current challenge is to universalize access to proper sanitation services, but resource recovery implementation could be part of this process. Based on the treatment configuration of the plants in this region some recommendations were made. For activated sludge plants (26% of the total) the recovery of phosphorus from the liquid phase from sludge dewatering liquor could be indicated. For stabilization ponds WWTP (38%), microalgae cultivation from the mainstream is suggested. The advantages are favourable weather in the region, and the barrier is that this process is still at pilot-scale.

Some key factors that affect phosphorus recovery implementation were identified in Paper I (Tables 4 and 5). They were classified as technical barriers: lack of decision-making tools and methodologies, product safety (risks-related), WWTP size; economic: market-value of the recovered resource, economic incentives, economic feasibility; social: public acceptance, stakeholders' perception; and political/institutional: legislation and regulations, lack of an integrated approach, and personnel skill limitations. All the challenges mentioned in Tables 4 and 5 should be addressed to encourage and accelerate the implementation of resource recovery solutions.

For instance, about the plant size, the cost per kg of P recovered varies according to the wastewater volume (daily flow rate) and P concentration. These costs are relatively higher for smaller plants and for lower discharge P concentrations (Otoo and Dreschsel, 2018). New business models, public policies, partnerships, educational measures, creation of networks, financing mechanisms, and incentives are necessary practices to facilitate planning and implementation. In this context, government subsidies towards P recovery or imposing taxes on extracted phosphorus (conventional fertilisers) are important measures (Li et al., 2019). Also, regulatory interventions like banning landfills to dispose of sewage sludge and/or recycling obligations can promote nutrient recovery and reuse (Rosemarin et al., 2020).

Regarding phosphorus recovery, struvite precipitation is a mature technology, however the market value of the product is not yet competitive to the conventional fertilizer. So, the next steps could be to develop the market, to reduce the production and operation costs, and conduct research on how to combine P recovery with other valuables recovery processes to increase profitability. Most full-scale WWTP with P recovery are in Europe and North America. Then, there is great potential for phosphorus recovery implementation in developing countries, such as those in the Latin America and Caribbean Region.

3.2. Case study about the Macrometropolis situation and the framework proposal (Paper II)

In developing countries, there is a lack of information and studies about resource recovery from wastewater to support the development of coherent policies in this area. Paper II contains an analysis and evaluation of possibilities and alternatives of resource recovery, especially reclaimed water, phosphorus, and energy, from wastewater treatment in the Macrometropolis of Sao Paulo, the main urban concentration of Brazil (Fig. 10).

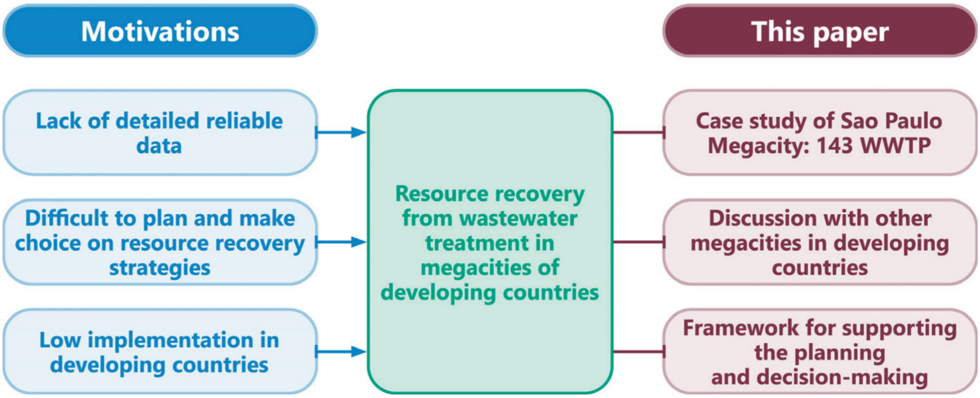

Fig.10. Graphical abstract of Paper II. Source: Chrispim et al. (2020b).

The main results are divided here based on the specific objectives of the paper: the findings from the questionnaires and analysis on how recovery practices vary across the study region; the key factors that affect the implementation of resource recovery; a proposed framework as a tool to stimulate/support planning and decision-making; possibilities for resource recovery strategies and improvements that could be implemented in the study area; and a comparison between the region of Sao Paulo and other megacities concerning resource recovery from wastewater treatment.

Regarding the situation of resource recovery implementation in the Macrometropolis, the results have revealed that only 26% of the plants performed at least one practice of resource recovery, and the predominant practice was internal reuse of water. Resource recovery initiatives were concentrated in larger plants and urban municipalities. Considering the existing plants with water reuse for external purposes, the production and commercialization of reclaimed water from treated effluent are relatively low.

Sewage sludge is disposed of in landfills, except for 3 plants that perform composting for use in agriculture (Fig. 11). Another important finding is that there is no energy recovery in the surveyed plants. Although several plants (21.7% of the total) produce biogas, it is not recovered (Table 1 of Paper II). Some managers reported interest in biogas recovery initiatives, expansion of reclaimed water production, and sludge recycling for agriculture or building materials; some of them provided more information about their current plans on resource recovery such as Campinas city, as reported in Paper II.

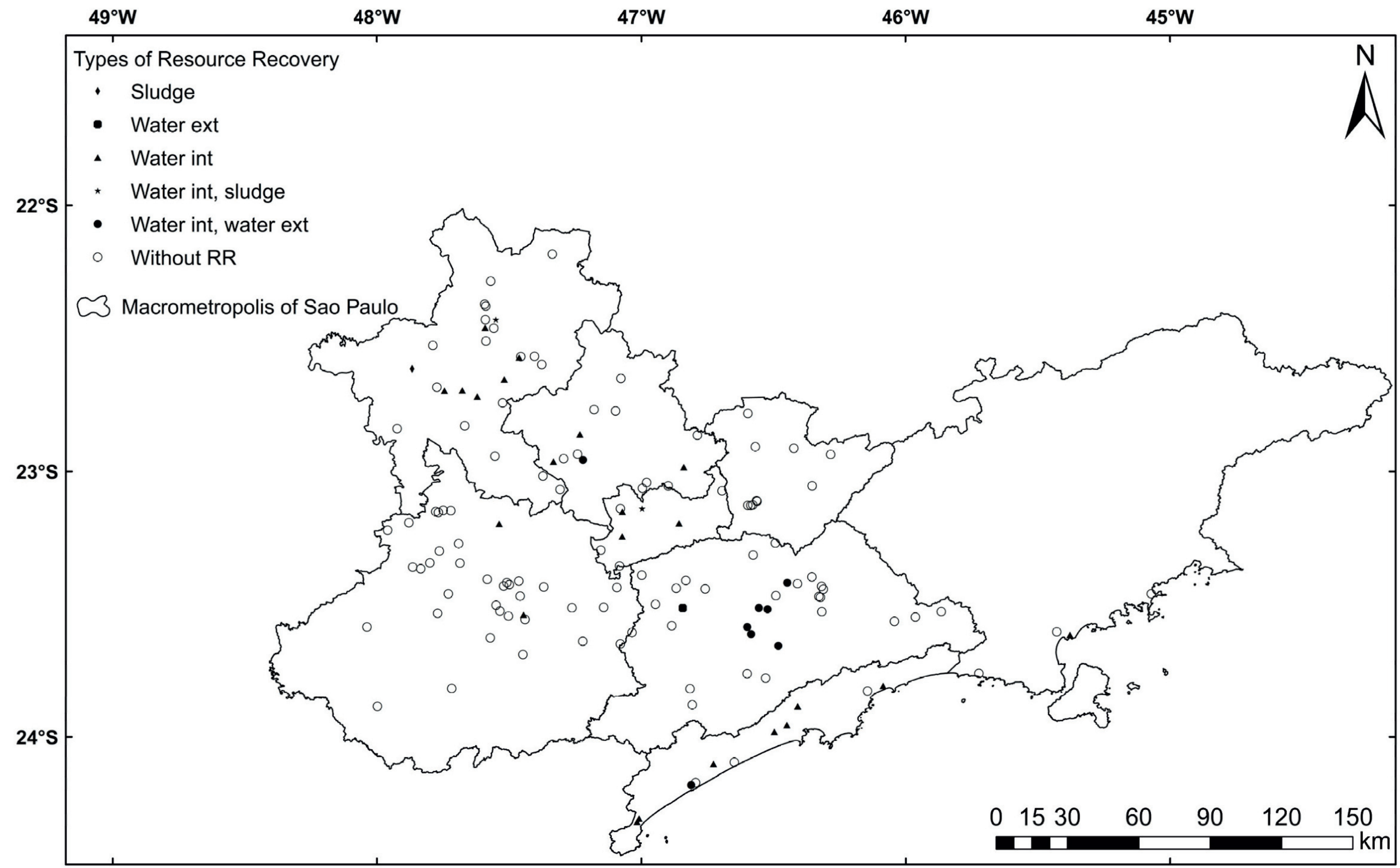

Fig. 11. Resource recovery measures in the study area in all the assessed WWTP. Source: Chrispim et al. (2020b). Water ext., external water reuse; water int., internal water reuse; water int., sludge, plant with internal water reuse and sludge recycling; water int., water ext., a plant with internal and external water reuse; RR, resource recovery.

Based on the consulted literature, the key factors that affect the implementation of resource recovery are the size of the plant, local legislation, and treatment technologies. These factors are discussed in the paper. For the Sao Paulo Macrometropolis case study some barriers are strict regulations about the application of treated sludge in agriculture; lack of incentives to support the introduction of the recovered products in the market; lack of technical knowledge of plant managers about resource recovery options; low demand for reclaimed water (from treated effluent) in the surrounding area of some plants; and low amount and quality of biogas produced in small plants. In general, some other identified barriers are little utility interest towards innovation and circular economy; no competitive price or no existing local market for the recovered product (e.g., struvite); and lack of incentive-based policies to integrate energy efficiency measures into WWTP.

Sherman et al. (2020) have conducted a similar research with utility managers, but in the United States, to understand the barriers to innovation in the municipal wastewater sector. They concluded regulations (e.g., water reuse standards) are relevant within the context of innovation, as many new technologies emphasize resource recovery and multi-sector benefits. However, in their study, the managers did not identify specific regulatory requirements, and the stringency of those requirements, as the main barrier to innovation. In this point, in their study, the managers highlighted the need for improved communication, collaboration, and increased flexibility to encourage innovation. Therefore, stakeholders interested in innovation could help wastewater utilities and regulators build solutions and better make decisions about resource recovery technologies. This kind of collaboration among stakeholders is part of our proposed framework.

The final section of the paper introduces a tool called a framework with several steps to help resource recovery implementation (Fig. 4 of Paper II). Also, the framework can support planning, decision-making, and assessment of resource recovery scenarios. The framework was derived from the survey and incorporated important factors such as the existing treatment characteristics and local conditions (e.g., demand for resources), and a set of sustainability indicators. Involving strategic actors (stakeholders) is important for scaling up, not only focusing on technological aspects, so stakeholders mapping and collaboration are part of the framework's steps. The proposed framework should be useful for decision-makers, and its application should facilitate the planning process, reduce the time for decision-making of resource recovery projects, and provide environmental and economic benefits.

Considering the results of our survey in the Macrometropolis region, the local conditions, and discussing them with the literature, we made several suggestions for improvement of resource recovery. Biogas recovery is suggested for the anaerobic plants (with co-digestion for the ones with low biogas production). Microalgae growth systems are suggested for pond systems, and the biomass could be used for several applications as shown by literature (energy production, biofuel, fertilizer).

For the plants with the Nereda process, recovery of alginate-like exopolysaccharides, and phosphorus recovery from sludge are recommended. The expansion of water reuse is recommended particularly for eleven municipalities of Piracicaba/Capivari/Jundiaí Basin which face a deficit of water supply for industrial purposes. Nutrient recovery solutions are especially interesting for the Metropolitan Region of Sorocaba due to predominant agricultural activity. Then, the planning and implementation of resource recovery could benefit the local economy of these metropolitan regions.

Other key presented data are regarding sewage collection and treatment in the study region. About 26% of the collected sewage is not treated and several municipalities still do not have treatment for their collected sewage. Just around 70.3% of the generated wastewater is collected and treated. So, expansion of proper sewage management is required in this area, particularly in the metropolitan regions MRSP and MRPVNC. In this sense, it is relevant to comment about irregular areas. According to IBGE (The Brazilian Institute of Geography and Statistics), 11% of the population of the Metropolitan Region of São Paulo lived in illegal/irregular urban areas (also called subnormal clusters or favelas) in 2010, corresponding to more than 2 million inhabitants (IBGE, 2010). It is estimated about 2,073 irregular occupations in São Paulo city (Instituto Trata Brasil et al., 2015). In terms of population, the cities of São Vicente (30,5%) and Guarujá (49,4%) are the ones with the highest percentage of people living in irregular areas (Instituto Trata Brasil et al., 2015). It is worth noting that some data (indexes and percentage) and surveys on collection and treatment of data sources do not consider irregular areas, which in some metropolitan regions have increased and it is difficult to measure. In this scenario, structural challenges such as sewage collection and treatment provision are priorities (Alcantara et al., 2020); further improvements like resource recovery would depend on it. Future studies on this topic are suggested in the Conclusions (Section 4).

The comparison of the results with other megacities in BRICS countries showed that their situation regarding resource recovery implementation is similar to our case study, highlighting a few initiatives of resource recovery in their wastewater treatment facilities. The potentials of water reuse, energy recovery, and nutrient recycling are briefly discussed in such megacities.

3.3. Framework application at a WWTP in Sao Paulo megacity and the potentials for resource recovery (Paper III)

A sustainable wastewater treatment plant (also called water resource recovery facility or biorefinery) uses less resources and is more efficient, recycle its wastes, integrates resource recovery solutions, generates financial returns, and presents a technological design and operation compatible with social, economic, and environmental characteristics of its surrounding areas (Pott et al., 2018; Robles, 2020). Figure 12 illustrates an example of a water resource recovery facility. This paper aimed to showcase the new framework for planning, implementation, and assessment of resource recovery strategies for a representative WWTP to support the transition of this plant to a water resource recovery facility.

Fig. 12. Illustration of a water resource recovery facility (biorefinery) with some resource recovery practices.

In this section, the main results are summarised, according to each specific objective: application of the steps of the proposed framework to support decision-making on resource recovery strategies; to recommend operational and technological strategies of resource recovery (nutrients and energy) for this representative facility, considering economic, technical, environmental, societal, and political indicators; and to identify strengths and potential improvements of the framework. The framework (Fig. 13) was applied in a large wastewater treatment plant in Sao Paulo Megacity.

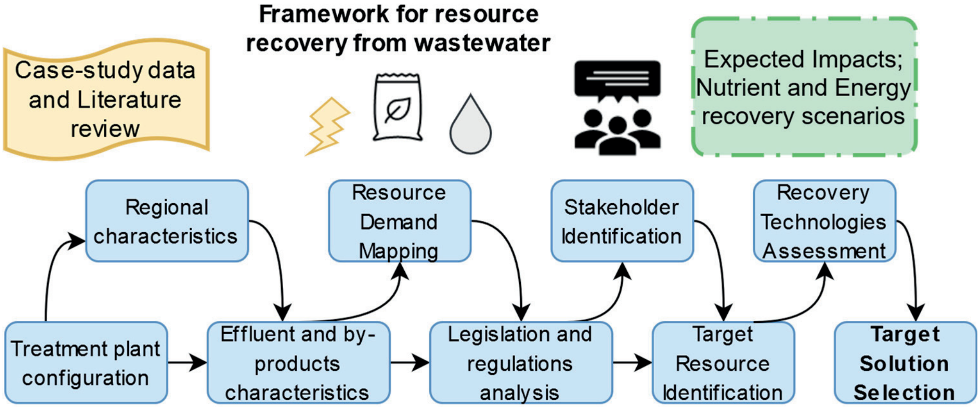

Fig. 13. Graphical abstract of Paper III, illustrating the main steps of the framework. Source: Chrispim et al. (2020c).

Treatment configuration; wastewater and by-products composition; potential demand for water, energy, and phosphorus; stakeholder identification and local legislation are factors that influence resource recovery decision-making and were thoroughly discussed. Step one consists of evaluating the existing treatment characteristics and the expected upgrades. This analysis is relevant when planning resource recovery strategies since the increase of the plant's capacity will imply an increase of generated by-products amount (e.g., sludge) and will have effects on characterization (effluent and sludge quality). From Step 2, the results showed a predominance of processing industries in the study area, and few cities with agriculture activity. Figure 4 of Paper III presents the distribution of economic activities in the studied region. The main processing industries are automobile, chemical, metallurgy, rubber and plastic production, food, and textile. They have a high demand for water as shown in Table 5. Thus, water reuse from treated effluent for industrial purposes is a promising solution in this region. There is already production of reclaimed water in the WWTP evaluated, but an expansion of this initiative, for example, to other plants and to more industries is recommended. Regarding agriculture, the urban community gardens as well as horticulture and floriculture settlements could be end-users of the recovered nutrients as fertilisers.

Analysing the waste stream composition is essential to the selection of suitable resource recovery technologies. Step 3 presents a quantification of the by-products generated in the treatment processes. Remarkably high amounts of sludge, grit, and screening material are generated and disposed of in landfills (112.9 ton/day, 3,175 kg/day, and 554.5 kg/day respectively). Results from Step 4 provide a good picture of the demands for water, nutrient, and energy in the local context as well as potential customers (e.g., industries, farmers) and local market value for the recovered products.

In Step 5, the legal framework and public policies are analysed. In the State of Sao Paulo, irrigation application for agricultural uses, grazing, and forestry is not included in the legislation on water reuse. Some barriers are lack of financial incentives to planning and implementation of water reuse projects. This agrees with Sgroi et al. (2018) who concluded that economics and the lack of funding are the main barriers to the development of water reuse worldwide. Municipal and regional plans present biogas for energy recovery as strategic measures to reduce greenhouse gas (GHG) emissions.

Regarding sewage sludge regulations, a new regulation (n. 498-CONAMA) has been recently published (Brazil, 2020) and has updated and revised the regulations 375/2006 and 380/2006 (National Environment Council, 2006a, 2006b). This regulation (n. 498) expands opportunities for the use of treated sewage sludge in soils, and in general, is more flexible than the previous ones (in terms of frequency of analyses, guidelines for application, and permitted uses). So, from now, it is expected that the practice of applying treated sludge for agricultural use can be more spread in the national territory, contributing to an effective and sustainable disposal.

Step 6 provides an identification of the relevant groups of stakeholders and how they can engage and work together in resource recovery projects. Lam and Van der Hoek (2020) claim that the building of partnerships between WWTP and other sectors is important to enable resource recovery and to sell the recovered products. Also, Weissbrodt et al. (2020) highlight the importance of university and WWTP utility partnerships as a beneficial strategy for both sides. It would be difficult that the WWTP tackle the challenging tasks of resource recovery planning and implementation alone, so collaboration is essential.

Based on the results of Steps 1 to 6, energy recovery and sludge management (e.g., nutrient recycling) showed a higher potential and were chosen as priorities. From step 7, suitable nutrient and energy recovery scenarios were analysed based on indicators. Table 6 of Paper III provides detailed information on the assessment of all resource recovery scenarios and Figure 14 offers an easier visualization for the scenario's assessment. For the studied plant, sewage sludge composting and biogas recovery showed more favourable conditions due to similar experiences in the area and robust legislation. Scenario B seems to be the most favourable for nutrient recovery due to low costs, high recovery potential, and less requirement for skilled labour. From a technical and environmental perspective, composting of sewage sludge is more favourable than struvite recovery for the analysed context. For energy recovery, biogas recovery is more favourable considering the set of indicators. Regarding Scenario D, developing countries usually have poor or no waste management infrastructure, therefore properly controlled co-processing can be a practical, cost-effective, and more sustainable option instead of landfilling. Co-processing of wastes provides energy and materials recovery during cement production (UNEP, 2011).

The choice of indicators and ranking of recovery options depend on the preferences of the decision-maker(s), which will be influenced by the local situation. Then, decision-making will depend on plant managers and stakeholders' preferences.

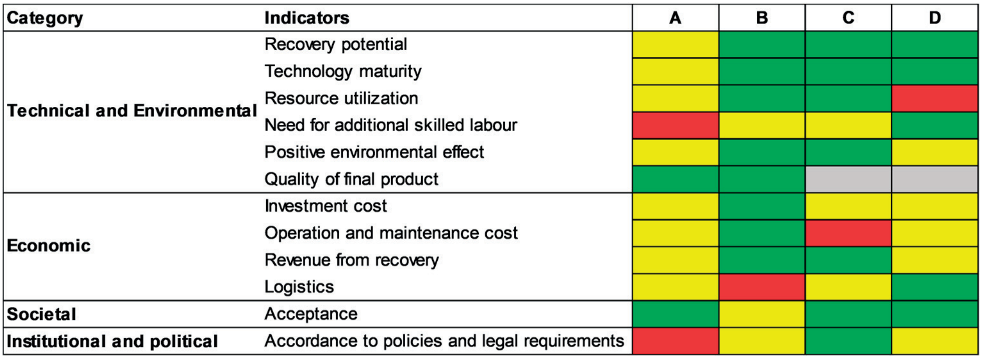

Fig. 14: Results of the comparison of resource recovery scenarios. A: Struvite recovery; B: Co-composting of sewage sludge; C: Biogas recovery from co-digestion; D: Energy recovery from co-processing of sewage sludge. Green corresponds to more favourable conditions when the value of the attribute under evaluation is not problematic (it is considered positive); yellow represents intermediate situations; and red is used when the value of attribute raises a potential problem (it could represent a negative situation). Gray: not applicable. More information on the assessment and quantitative values are in SM 4. Source: Chrispim et al. (2020c).

Considering the case study WWTP, the paper provides estimates on recovered resources as struvite, electricity recovered through co-digestion, and thermal energy recovered from co-processing in cement industries. The fertilizer or soil conditioner products (scenarios A and B) could be used for several applications such as landscaping in agriculture to restore degraded land or to cultivate crops, sugarcane, eucalyptus, ornamental plants, coffee, and vegetables. The electricity produced by scenario C would be used to supply part of the internal demand of the WWTP, while in scenario D, the recovered energy would be used by cement industries.

The strength of the framework when compared to other frameworks, is that it includes more indicators and involves a variety of stakeholders, is more comprehensive, and offers descriptive instructions on how to approach each step. Thus, the new framework has a practical value and stimulates plant managers to think about new potential solutions by providing relevant information. After testing the framework, some suggestions of improvement are given, such as to change the order of some steps to facilitate data collection and speed up the process, to limit the scale of analysis to a smaller area, and to adapt the framework for application in different contexts (e.g., WWTP in urban or rural areas) and for other target resources.

Besides the case study in Sao Paulo megacity, Paper III provides an assessment of the potential application of the framework to other megacities. Mexico City, Johannesburg, and Delhi have a high level of applicability, and the expected impact of the framework application varied from medium to high in such megacities. This is related mainly to the high demand for potential resources (e.g., water and energy) in these megacities. The assessment considered not only the demand (and use) for water, energy, and phosphorus, but also if there has been an increase in the resource consumption (e.g., electricity), its current availability and if it represents a key issue for the city.

Some lessons learned from the case studies in Papers II and III are the key variables that affect resource recovery implementation (e.g., plant size, legislation, among others), suitable resource recovery technologies and potentials based on the existing treatment processes, and a new tool for supporting planning and decision-making, including what aspects need to be considered to a successful implementation.

3.4. Biogas for energy recovery: recent trends, research gaps, and conditions for implementation (Paper IV)

This paper is a literature review on energy recovery from biogas in wastewater treatment plants. The results summarised here are based on the submitted manuscript (Chrispim et al., 2021). Recovering energy from sewage and sewage sludge is not only an efficient way to produce renewable energy, but also an effective measure to mitigate climate change by reducing greenhouse gas emissions. Wastewater treatment plants are the most energy-intensive public operation in most towns in the developed world (Daneshgar et al., 2018), so measures to reduce energy consumption and improve energy recovery in such facilities are very important.

There are many techniques to recover energy from wastewater, but in this paper, the focus was on biogas from anaerobic digestion. Energy self-sufficient WWTP refers to a WWTP generating 100% or more of the energy it needs for its operation solely from the energy embedded in the water and wastes it treats, with zero external energy supply (Svardal and Kroiss, 2011; Gu et al., 2017). This concept has emerged recently and became a global hot topic among researchers worldwide (Passos et al., 2017; Gu et al., 2017) and has been part of the goals of several utilities worldwide (Lam and Van der Hoek et al., 2020).

However, particularly in developing countries, the progress towards energy recovery from wastewater has been slow. The specific objectives of this paper were to give an overview of recent techniques to enhance biogas production, particularly co-digestion and microalgae-based treatment systems; to identify applications of biogas recovery in full-scale wastewater treatment plants, particularly in developing countries; and to understand how local factors may affect the implementation of energy recovery in three megacities of developing countries. Figure 15 summarises the main topics addressed in this paper.

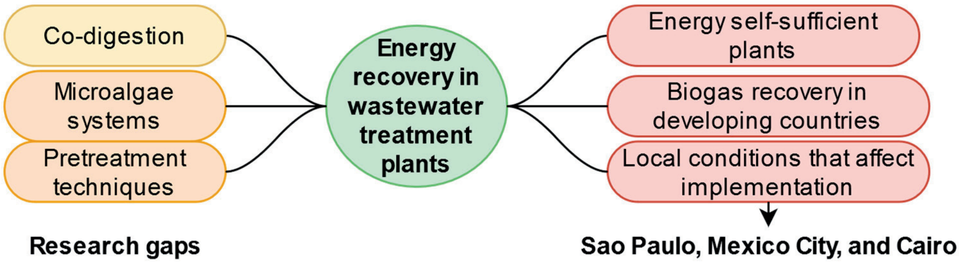

Fig. 15. Main content of Paper IV.

In this paper, the main technologies for enhancement of biogas production are discussed. Pretreatment methods enable the improvement of the organic material's availability, by enhancing the biodegradable organic fraction of the sewage sludge (Mirmasoumi et al., 2018; García-Cascallana et al., 2019). Examples of thermal hydrolysis studies are given in the paper and report an increase of biogas production and consequently electrical energy production. The research gaps identified to thermal hydrolysis are high energy requirements; evaluation concerning the overall environmental impact; synergy between effluent quality and energy production; and reduction of costs.

Co-digestion is a suitable measure to increasing the organic loading rate (OLR), biogas production, improving nutrient balance in the process and diluting inhibitive substances (Grosser and Neczaj, 2018; Arhoun et al., 2019). Several studies have combined different substrates with sewage sludge (food waste, agro-industrial wastewater) and presented increases in biogas production. Co-digestion is a good strategy to optimize the anaerobic digestion process and contributes to a WWTP to reach energy self-sufficiency. Some identified research gaps for co-digestion are the need for large-scale and long-term studies, effects of co-digestion in the overall GHG emissions, and characteristics of substrates.

Biomass from wetlands or microalgae growth systems have gained attention recently and can be used as a substrate for co-digestion with sewage sludge or other organic substrates (e.g., swine manure). The reviewed studies showed that co-digestion of microalgae and sludge improve methane productivity compared to each substrate mono-digestion. Other benefits from biomass production through microalgae are the reduction of energy demand and assimilation of CO_2. There are some constraints related to microalgae for energy recovery such as seasonal conditions, and remaining research gaps (e.g., economic feasibility, operational conditions, harvesting techniques, long-term studies). Table 1 of Paper IV presents all the identified research gaps.

The paper also addresses several examples of energy recovery from wastewater worldwide, including full-scale and energy self-sufficient WWTPs. Most analysed energy self-sufficient WWTPs use biogas from anaerobic co-digestion of sludge for digester heating and electricity generation, and some of them apply pretreatment methods (e.g., thermal hydrolysis) as strategies to enhance biogas production. Besides energy recovery, the use of digestion by-products (digestate and digested sludge) as organic fertiliser in agriculture can provide environmental and economic benefits.

As noted in Table 2 (Paper IV), there are some examples of energy recovery plants in developing countries. The potential of biogas in sewage sector is few explored, for example, in Brazil and Mexico. In developing countries, biogas requires further advances for large-scale implementation of energy recovery for electricity generation, and for use as fuel for transportation. More populated cities are more viable to exploit biogas produced in WWTPs because of larger volumes of produced sewage, more generated biogas and produced electricity (Campello et al., 2020). Also, these large plants usually count with more infrastructure, for example, anaerobic digesters, than medium or smaller plants, which minimizes investment costs and the need for skilled labour for energy recovery implementation.

From the assessment of local conditions that influence energy recovery in megacities (Table 3 of Paper IV) we can highlight the need for renewable energy policies and incentives to promote implementation. Further policies with clear incentives and specific legislation to biogas recovery are needed so energy recovery projects can be created and expanded in developing countries. These findings agree with the literature in this field (Mainardis et al., 2020; Díaz- Trujillo et al., 2019; Gustafsson and Anderberg, 2021). The variables assessed by our paper are electricity prices, the proportion of fossil fuels used, the electricity generation mix, the regulations limiting emissions, the landfill costs, the government subsidies, the number of plants with anaerobic digester, and the plant capacity. Our results indicated that most of the variables are favourable to promote energy recovery in the three assessed megacities. We recommend some of the variables to be managed or further developed; this is the case of government subsidies (for all three megacities), plants with anaerobic digesters and electricity prices (for Cairo), and landfill costs (for Sao Paulo). Also, in Table 5 (Paper IV) we recommend the following main strategies: to promote energy recovery and face the identified challenges: to promote funding and financial incentives to WWTP, create well-target renewable energy policies, and multisectoral partnerships.

The analysis of local factors provides useful information to identify the current challenges and guide better planning and decision-making. This also can be used to support assessments in other megacities or for comparison purposes. Energy recovery implementation in these urban areas can contribute significantly to meet their national or regional targets related to climate change and sustainable development (e.g., Sustainable Development Goals).

3.5. Communication of the results and expected impacts on the Sustainable Development Goals

The communication of the main results to local stakeholders is an important step to deal with some challenges, enhance market and social acceptance, promote education and awareness about resource recovery potential, and consequently, cultural changes. The results of Paper II were shared with representatives of several organisations. Firstly, the wastewater treatment plant managers in the study region received a copy of the paper and were invited to join an online event for knowledge exchange, where the main results of Papers II and III will be explained.

Also, the Paper II was shared to other relevant stakeholders from different sectors: 2030 Water Resources Group from the World Bank (who acts in partnership with the local water utility to optimization of the WWTPs in Sao Paulo Metropolitan region and conduct projects related to water security); Waste2Resource initiative (from the World Bank); Instituto Trata Brasil (Civil Society Organization of Public Interest, formed by companies with an interest in the advances in basic sanitation and in the protection of water resources); C40 Cities Climate Leadership Group (non-profit organization which has network on waste to resources); research groups within the same field in USP and other universities, the national network of Sustainable Wastewater Treatment plants, Macroamb (project on Sao Paulo Macrometropolis), Thematic Group of Sewage Treatment of ABES - Brazilian Association of Sanitary and Environmental Engineering; Observatorio das Metropoles (representative of a project on urban water management in metropolitan regions). This step had the purpose to provide key information that practitioners (e.g., members of wastewater utilities) can consider when implementing resource recovery projects, and academic community can use to developing related research. This kind of initiative (communication of scientific results) makes the research available, reaches a broad audience, and improves the likelihood of knowledge utilization (e.g., the framework application) in the real world.

From this study results, an impression was created that currently, the plant managers have not much interest in developing resource recovery because there is a lack of incentives and the decision-makers need more knowledge on resource recovery solutions. In Paper III, we identified the potential stakeholders, their main roles, and suggested how they could engage and contribute with the process. We think this research result is an important first step that can motivate them, so they could start a collaboration.

As resource recovery is a multidisciplinary topic and related to several aspects of sustainability, we assessed how this research/thesis could impact the Sustainable Development Goals (SDG) (Fig. 16). Resource recovery solutions and our results can impact positively 9 SDG, being 4 goals directly (clear water and sanitation; affordable and clean energy; sustainable cities and communities; responsible consumption and production) and 5 goals indirectly (zero hunger; industry, innovation, and infrastructure; climate action; life below water; partnerships for goals). This indicates a clear contribution and the connections of this research with sustainability.

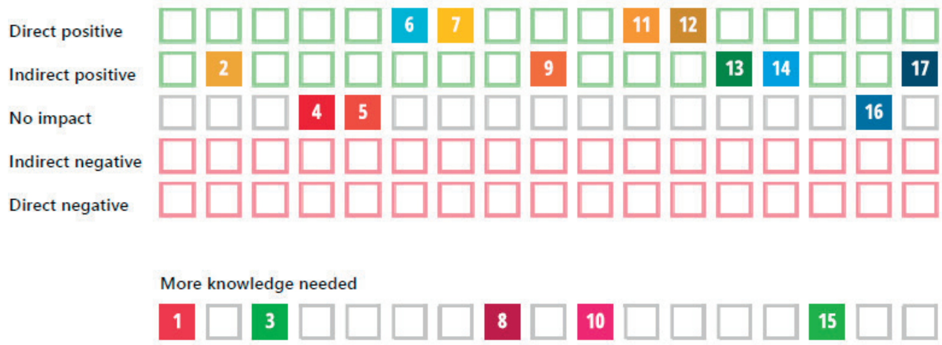

Fig. 16. Impacts of this thesis on the Sustainable Development Goals, based on a self-assessment using the SDG Impact Assessment Tool (Chalmers University of Technology et al., 2020).

4. Conclusions and recommendations for future work

The main conclusions and suggestions for future work are divided into four parts, based on each one of the appended papers. Finally, general conclusions are provided.

Regarding Paper I, the most common process for Phosphorus recovery is struvite precipitation, particularly for secondary streams. This process is still expensive compared to conventional phosphate fertilizer production. The implementation of P recovery at full-scale is concentrated in developed countries. Based on the assessment of technologies, recovery from the liquid phase generates fewer emissions and has lower energy demands but has lower rates of recovery compared to recovery from the solid phase (sludge and ashes). Developing and low-income countries should consider simple and cost-effective methods (high recovery rate, no specialized labour, and no large space need). The Latin America and Caribbean region has a great potential to implement phosphorus recovery in existing and new treatment facilities. Processes from the liquid phase are suitable for activated sludge plants while microalgae cultivation could be applied in stabilization pond systems. Implementation of resource recovery from wastewater in developing countries could generate many environmental, economic, and social benefits and contribute to these countries achieve their water and sanitation goals (and other related Sustainable Development Goals). Several technical, social, economic, and political/institutional barriers should be addressed to allow progress towards the implementation of phosphorus recovery.

Suggestions for further research:

- Economic feasibility of P recovery processes.
- How to improve the performance of P recovery processes (e.g., recovery efficiency).
- Valorisation of potential by-products from P recovery processes (e.g., from sewage sludge ashes processes: aluminium, silica sand) and possible applications (e.g., construction industry).
- Diversification of phosphorus recovered product (e.g., calcium phosphate) applications (e.g., high-purity products as additives for animal feed, and food and beverage industries).

- Environmental impacts (e.g., reactants and energy demand) related to recovery processes should be further evaluated.
- To investigate how to integrate stakeholders' perspectives (e.g., end-users) in planning and decision-making processes.
- To approach educational measures to increase public acceptance of the products derived from wastewater.
- To study how to face the identified barriers to implementation.

From Paper II, we can draw the following conclusions. The study area (Macrometropolis of Sao Paulo) presents a low implementation of resource recovery, but our results also show a great potential to expand the strategies of resource recovery, either for new plants or for retrofitting the existing ones. In the Macrometropolis of Sao Paulo, water reuse for internal purposes is the predominant recovery practice. Partnerships between water utilities and universities and with private companies can help to achieve a successful implementation, as shown for the cases with nutrient recycling from sewage sludge. Priority areas with higher potential for water reuse and/or nutrient recovery are identified across the study region. The main factors that affect implementation are local legislation, perception of stakeholders, public acceptance, plant size, location (urban/rural), lack of technical knowledge about recovery technologies, and the existing treatment configuration. Resource recovery measures are not commonly implemented in wastewater treatment plants in developing countries, as addressed in the paper for Brazil, China, Russia, and South Africa. Incentive-based policies are important to stimulate the interest of water utilities in the implementation of resource recovery technologies. All the identified factors should be addressed in an integrated way to allow for progress in resource recovery implementation. The proposed framework considers these key factors and offers useful procedures for thinking, planning, and decision-making on potential resource recovery measures.

Suggestions for further research:

- To study how to expand resource recovery solutions to small WWTP.
- To develop energy recovery projects in the existing and new WWTP in the study area.
- To focus on illegal occupations/settlements to get a more precise and realistic picture of the sanitation issues faced by these urban areas, by searching wastewater collection and treatment coverages and how they could be improved.
- To identify local barriers in other megacities.
- To analyse the effects of government incentives and legislations related to resource recovery.

- To establish a global or regional (e.g., by continent) inventory of real situations/practices of resource recovery and identify areas with higher potential.
- To combine other methodologies (e.g., Life-cycle assessment (LCA), Cost-benefit analysis, City Blueprint Approach, Urban Growth models, Social-ecological systems analysis) with the proposed framework.
- To apply the framework in regions with similar (or different) conditions from our case study.

Paper III led to the main following conclusions based on the framework application. Legislations on water reuse and sewage sludge reuse in agriculture have some restrictions, which may hinder these practices in the study region. Based on the assessment from framework application, co-composting of sewage sludge and energy recovery from biogas are the most suitable solutions and show a more favourable environment to implementation. The main benefits provided by the implementation of the suggested recovery scenarios are the improvement of effluent quality, lower CO_2 emissions, reduction in global warming potential, and reduction of waste generation. The WWTP produces quantity of treated effluent sufficient to meet all the irrigation and industrial demands in the region, and the estimated struvite recovery for this plant could supply the total demand for phosphate fertilizer in the study area. The application of circular economy vision to the wastewater sector through resources recovery benefits also other sectors such as energy, industries, and agriculture. Detailed guidelines and insights are provided in each step of the framework. Then, it is expected it can facilitate the planning and decision-making processes in urban areas.

Suggestions for further research:

- To test and evaluate struvite recovery technologies at pilot-scale in WWTP in the study area.
- To monitor the quality of supernatants and sewage sludge produced in WWTP, and to research the optimal operational conditions for resource recovery.
- To survey the local market needs (e.g., what kind of products do they have interest in?) and public acceptance for the recovered products.
- To develop business models to support implementation of different resource recovery solutions.
- To educate the plant managers and policymakers so they can develop a long-term thinking and be more aware and interested in resource recovery.
- To update the framework application in the studied WWTP in the future and apply it in other plants in Sao Paulo megacity.

- To apply the framework in other contexts (e.g., the suggested megacities in Table 2) and to test the suggested improvements (Section 3.2.2 of Paper III).
- To study how a recovery process or different treatment configurations would affect other recovery processes (e.g., whether phosphorus precipitation for P recovery affects biogas production for energy recovery) and how to optimize resource recovery in WWTP.
- To explore the stakeholder's engagement and cooperation through the framework application.

Paper IV focused on energy recovery and the main conclusions are summarised as follows. There are many possibilities to improve energy efficiency in wastewater treatment. Several examples of energy self-sufficient plants are given and most of them are based on biogas recovery from anaerobic co-digestion for electricity generation. Co-digestion and microalgae systems can contribute to increasing biogas production and remaining research gaps were identified. In developing countries, the progress on biogas recovery from wastewater and sewage sludge has been slow. The assessment of local conditions enables to analyse what needs to change to promote energy recovery from biogas in Sao Paulo, Mexico City, and Cairo megacities. All of them need to strengthen their policies and subsidies related to climate change and energy recovery. In the case of Sao Paulo, electricity mix with low emissions factor and low relative landfill costs can hinder energy recovery implementation. In Cairo, low electricity prices, lack of government subsidies to renewable energies, and few anaerobic digester infrastructures can hinder implementation. In all the three megacities, most of the local conditions influence positively the implementation of energy recovery, which indicates they show a high potential to apply it. We concluded that funding for energy recovery projects in WWTP and creation of multisectoral partnerships with key stakeholders are the main important strategies to enable energy recovery in cities of developing countries. Overall, our results can support the incorporation of biogas recovery in WWTPs and give insights to future research on the enhancement of biogas production.

Suggestions for further research:

- To perform full-scale and long-term studies of the evaluation of characteristics of harvested microalgal biomass.
- To investigate the quality of digestate and biosolids resultant from co-digestion.
- To monitor operational conditions and investigate synergistic effects at system-level of co-digestion and microalgae systems.
- To analyse the overall environmental impact of thermal hydrolysis as pretreatment and its energy demand.

- To map and evaluate the potential of energy recovery from biogas in Upflow Anaerobic Sludge Blanket Reactor (UASB) plants for energy recovery in developing countries.
- To investigate in more detail the influence of each variable (or others) in energy recovery implementation in each megacity.
- To explore the maximum potential of energy and resource recovery from wastewater and its by-products.

General conclusions

The transition to resource recovery in the wastewater treatment sector is a gradual process and involves several challenges. This thesis addresses what needs to change to implement resource recovery strategies from the wastewater sector, particularly in megacities of developing countries. This is the first research to analyse the current situation of WWTP and investigate possibilities of resource recovery in a comprehensive way, in the Brazilian context, using a holistic approach (e.g., integrating the sustainability dimensions).

The results of this research provide an overview of the situation of WWTPs in the assessed megacities regarding resources recovery, in detail for the Sao Paulo region. We concluded there is a high potential for nutrient and energy recovery in developing countries, where few practical examples of resource recovery are available currently. The identified barriers and local factors are useful information to the elaboration of resource recovery projects and provide guidance for wastewater treatment companies about how to plan configurations for improving the existing WWTPs and designing new plants. The lack of local regulations and incentive mechanisms, as well as economic feasibility of recovery processes, seem to be the main current challenges to full-scale phosphorus recovery implementation. For energy recovery, the main barriers identified are lack of government incentives, and existing technology and infrastructure. The methodology used in Paper II can assist in the monitoring of the circular economy implementation in the water sector in urban areas, and the proposed framework (Paper III) can support planning and implementation of resource recovery practices in WWTP.

The proposed framework should be useful to managers and decision-makers and its application enables them to cope with the identified barriers facilitating resource recovery implementation. We tested the framework in a real case and performed indications of improvements as well as suggestions for application in similar megacities.

Regulations and the involvement of strategic stakeholders are important measures for scaling-up resource recovery strategies. Mapping of end-users for the recovered products is also challenging, for instance, in the case study region and likely in other developing countries, the product (e.g., struvite) is not well-known by the farmers.

In this sense, it is important to engage the end-users (consumers) to know their prerequisites regarding the recovered products (e.g., in terms of quality and price). Thus, enhancing social acceptance by promoting demonstration sites to show the safety and quality of the product is especially important. Yet, developing business models for resource recovery solutions of local interest (e.g., define who is responsible for each step of the value chain) is also required for implementation. All these strategies could be combined with the framework application. Further research is needed in these aspects, particularly in the study area (Sao Paulo region). We also recommend for developing countries the development of a national strategy for nutrient management and use; such strategy is already in use in for example Sweden and Switzerland (e.g., nutrient platforms). These platforms could work as spaces for exchanging knowledge on nutrient recovery solutions, and for cross-sectoral collaboration and discussion.

The introduction of resource recovery solutions such as those discussed in this research can contribute to a shift from linear to a circular economy. Considering that meeting the water needs of fast-growing cities is an especially important and current challenge globally, wastewater treatment plants with resource recovery technologies can generate many environmental, social, and economic benefits, they can for example not only provide alternative water source from the treated effluent but also provide energy and valuable products. Moreover, resource recovery from wastewater is important to generate resilient and sustainable cities, which are prepared to adapt to climate change. Based on the assessment using the SDG Impact Assessment Tool, the results of this thesis can contribute positively to nine SDG (Figure 16). This highlights the connections of this research with sustainability and possible impacts on society.

In this view, wastewater treatment plants can play an important role for achieving sustainable development and are no longer conceived as service providers only, but also as resource recovery facilities. The resource-oriented sanitation approach has the potential to boost improvements in wastewater treatment infrastructure and universalization of proper sanitation access in developing countries. Additionally, resource recovery can support economic development. The knowledge generated in this thesis could be applied to improve the lives of local communities and impact society through the benefits from a better water resources management and resource recovery implementation (e.g., reduction of waste and pollution, and an increase of recycling).

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Review

Phosphorus recovery from municipal wastewater treatment: Critical review of challenges and opportunities for developing countries

Mariana Cardoso Chrispim[a,b], Miklas Scholz[a,c,d,*], Marcelo Antunes Nolasco[b]

[a] Division of Water Resources Engineering, Faculty of Engineering, Lund University, P.O. Box 118, 22100, Lund, Sweden
[b] Sustainability Graduate Program, School of Arts, Sciences and Humanities of University of Sao Paulo, Sao Paulo, Brazil
[c] Department of Civil Engineering Science, School of Civil Engineering and the Built Environment, University of Johannesburg, Kingsway Campus, PO Box 524, Aukland Park, 2006, Johannesburg, South Africa
[d] Civil Engineering Research Group, School of Science, Engineering and Environment, The University of Salford, Newton Building, Peel Park Campus, Salford, M5 4WT, UK

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ABSTRACT

The aim of this paper is to provide guidance in selecting phosphorus recovery options within the municipal wastewater treatment sector regarding developing countries. This critical review includes a brief contextualization of the resource-oriented sanitation paradigm, the discussion of processes for phosphorus recovery based on methods at full-scale, pilot-scale and laboratory-scale, and a concise discussion of the environmental impacts and benefits associated with phosphorus recovery strategies. Finally, the main challenges related to the implementation of resource recovery strategies, especially for phosphorous, were identified and discussed. According to the results, some of the main drivers for phosphorus recovery are the limited availability of phosphorus, increasing cost of phosphate fertilizers and reduction of maintenance costs. Currently, most of the operational processes are based on crystallization or precipitation from the digester supernatant. Struvite is the most common recovered product. The recovery rate of phosphorus from the liquid phase is lower (10–60% from wastewater treatment plant influent), than from sludge (35–70%) and from sludge ashes (70–98%). Phosphorus recovery remains challenging, and some barriers identified were the integration between stakeholders and institutions, public policies and regulations as well as public acceptance and economic feasibility. In developing countries, the implementation of nutrient recovery systems is challenging, because the main concern is on the expansion of sanitation coverage. Resource recovery approaches can provide benefits beyond the wastewater treatment sector, not only improving the sustainability of wastewater treatment operations, but generating revenue for the utility provider.

1. Introduction

The agriculture sector uses about 70% of the world's water resources for irrigation (National Science Foundation, 2014). Natural resources such as water are becoming scarce, and consequently, their efficient use and reuse becomes more attractive (Van Der Hoek et al., 2016).

The availability of nutrients (mainly nitrogen, phosphorus and potassium) and water limits the food production industry to meet the planet's demand. Phosphorus (P), an essential nutrient, is a finite resource obtained mainly from rocks located in few regions of the world. Morocco, for instance, controls 75% of the remaining world's phosphorus reserves (Cordell and White, 2015). This creates vulnerability to food production systems and increases the need to encourage sustainable phosphorus production practices (Cordell and White, 2015).

Therefore, some practices that contribute to sustainability in agricultural production and sanitation are the use of alternative sources of water; the increase of reuse practices and the recovery of nutrients from sewage systems (Ganesapillai et al., 2015). Thus, to utilize the limited resources efficiently, processes can be used to recover and recycle nutrients present in sewage to return to the soil, subsequently improving agricultural production.

The nutrient loop involves agricultural production, processing, consumption, and collection/treatment of waste (including wastewater). Then, the nutrients, if recovered from wastewater, can return as valuable organic and mineral compounds to agriculture, closing the loop (McConville et al., 2017). Alternative sources of nutrients are domestic and municipal wastewater. It is estimated that, globally, the total phosphorus content excreted by humans (just considering available phosphorus from faeces and urine) could meet 22% of the phosphorus demand (Mihelcic et al., 2011). In conventional domestic

* Corresponding author. Division of Water Resources Engineering, Faculty of Engineering, Lund University, P.O. Box 118, 22100, Lund, Sweden.
E-mail addresses: mariana.chrispim@usp.br (M.C. Chrispim), miklas.scholz@tvrl.lth.se (M. Scholz), mnolasco@usp.br (M.A. Nolasco).

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wastewater, over 80% of nitrogen and 50% of both potassium and phosphorus come from urine (Beler-Baykal et al., 2011). With regard to wastewater treatment, it is worth noting that the objectives (where present) have generally been the removal of carbonaceous organic matter, total suspended solids, chemical pollutants, excess nutrients and pathogens before disposing the effluents to the environment (Tchobanoglous et al., 2015; Verstraete et al., 2009). However, recycling of resources such as nutrients through recovery processes is an emerging objective due to environmental and economic motivations such as reducing drinking water consumption and generating revenue for the wastewater treatment works (Mehta et al., 2015; Rao et al., 2017).

In this context, resource-oriented sanitation is an approach that focuses on the recovery of resources, prioritizing water reuse, energy recovery and recycling of sewage constituents such as nitrogen, phosphorus and organic matter (Morandi et al., 2018). This view assumes that wastewater treatment plants will be replaced by water resources recovery facilities (World Bank Group and Development Bank of Latin America, 2018). This term is used to refer to the few treatment plants that have these resource recovery practices (Fernández-Arévalo et al., 2017).

Gijzen (2001) reports on the difficulty of identifying wastewater as an input of value, since after the treatment process, the effluent is not easily recognized as a valuable product (unlike water treatment for water supply). In relation to many developing countries, the investment in collection and especially in the treatment of sewage has been low. For example, a recent study coordinated by the National Water Agency (ANA, 2017) reports that in Brazil only 43% of the population has wastewater collected and treated, and 70% of municipalities do not have a wastewater treatment plant. So, the current challenge is how to universalize the access of sanitation infrastructure to the population. If the treatment process, besides improving the quality of the effluent, could generate value-added products, it would represent an important incentive to the effective operation and maintenance of these treatment units (Gijzen, 2001). There is an opportunity to increase the sanitation access through building of new treatment plants, but also simultaneously to implement resource recovery strategies in these facilities. Therefore, to practice sustainable management of domestic, municipal and industrial wastewater in cities means not only to treat sewage before discharging, but also to consider the potential of resource recovery implementation (Elser and Bennett, 2011; Zhang et al., 2015).

In order to make waste management more efficient within an urban area, it is important to identify problems and possible opportunities (dos Muchangos et al., 2017). Mo and Zhang (2013) argue that although there are several studies that have already looked at individual resource recovery methods and the potential for resource recovery in an integrated way, there are few scientific publications reviewing the current sustainability status of these methods and assessing their integration at different scales.

It is intended that this paper contributes to the collection of organized information about the phosphorus recovery technologies, identifying the main challenges and the reasons why the recovery of resources is still little implemented in wastewater treatment plants. In addition, it is expected that this critical review supports the planning for alternatives on how to recover resources in these facilities. Particular reference will be made to developing countries, helping decision-makers to learn from established technologies of phosphorus recovery.

The aim of this critical and systematic review paper is to provide guidance in selecting phosphorus recovery options within the municipal wastewater treatment sector, particularly in the context of large cities in developing countries such as the Community of Latin America and Caribbean States (CELAC). The objectives are to (a) assess technologies to recover phosphorus from the liquid and solid phases of wastewater; (b) discuss potential products linked to the recovery options; and (c) analyse the barriers to resources recovery from municipal wastewater. The definition of "recovery" considered in this review paper refers to the production or extraction of any material from the operations of wastewater treatment plants (solids, semi-solids and liquids; gases; nutrients; algae; treated effluents; and thermal or hydraulic energy (based on Shore (2017)).

2. Methodology

The critical literature review was carried out based on using the databases Scopus, Web of Science, Aquaculture Compendium, Emerald Insight, Integrated Search Portal (SIBI/University of Sao Paulo (USP)), Scielo and Science Direct. The applied search terms were as follows: "resource-oriented", "sanitation" and "concept"; "resource oriented sanitation"; "resource oriented sanitation approach"; "resources-oriented approach" and "sanitation" or "wastewater treatment"; "productive wastewater treatment"; "resource recovery" and "wastewater treatment" and either "nutrient" or "energy" or "nexus". Key textbooks on the subject were also consulted (Stamatelatou and Tsagarakis, 2015; Tchobanoglous et al., 2015; Val Del Rio et al., 2017). In addition, another search (in Scopus database) was performed, limited to developing countries, using the following terms: "nutrient recovery" and "wastewater" and "developing countries" to search for applications of nutrient recovery technologies, and the terms "wastewater technologies" and "Latin America" or "Latin America and the Caribbean". The website of Eawag (2019) was also consulted. Their publications on nutrient recovery projects in developing countries were reviewed. These documents were not resultant from the described searches but contain relevant and specific information to discuss the context of nutrient recovery in some developing countries.

Regarding the identification of phosphorus recovery technologies, the following procedure was adopted. A more specific search on the databases Web of Science and Scopus were performed using the following keywords and expressions: "phosphorus recovery" and "liquid phase" and "wastewater"; "phosphorus recovery" and "liquid phase"; "phosphorus recovery" and "liquid phase" and "municipal wastewater"; "phosphorus recovery" and "wastewater" and "solid phase"; "phosphorus recovery" and "wastewater" and "sludge"; "phosphorus recovery" and "sludge" and "municipal wastewater"; "phosphorus recovery" and "wastewater" and "ash"; "phosphorus recovery" and "sewage sludge ash". After these searches, technologies were selected based on the papers found and according to the specific recovery technique used. In addition, the following grey literature was consulted to obtain important information that did not show up in journal papers: the websites of the companies that developed phosphorus recovery technologies were consulted to complement some information about the technologies; reports from the website of the European Sustainable Phosphorus Platform (2014) was accessed to evaluate the phosphorus recovery technology inventory (Kabbe, 2017). Reports by the United Nations (UN-Habitat, 2008; United Nations, 2017), Inter-American Development Bank (2017) as well as the databases of FAO (FAO, 2017), International Fertilizer Industry Association (IFADATA, 2017) and Appleton and Notholt (2002) were consulted to obtain specific data about wastewater treatment and phosphorus consumption and demand in the target countries.

Then, the publications were assessed according to the phosphorus recovery technologies applicable for each phase (liquid or solid, and the latter was sub-divided into sewage sludge and ashes). Overview tables were created to assist in the identification of the main challenges and opportunities for resource recovery implementation.

3. Environmental impacts of wastewater treatment systems

Wastewater treatment eliminates organic matter as well as removes or inactivates pathogenic organisms present in the plant influent. The purpose is to stop the spread of diseases and to protect the environment against pollution (Batstone et al., 2015). A further objective of wastewater treatment should be resource recovery and sustainability (Andersson et al., 2018).

Despite the human and environmental health benefits provided by wastewater treatment plants, these facilities have the potential to become generators of great environmental impacts, affecting soil, air and water. Treatment plants generally require wide areas, have high energy and chemical consumption rates, produce liquid waste, release various pollutants into the atmosphere, and produce solid wastes that require proper treatment and disposal (Lins, 2010; Puchongkawarin et al., 2015; Zhang et al., 2015).

The stages of conventional wastewater facilities usually consist of preliminary, primary, secondary and tertiary treatment. At all stages, environmental impacts are generated; for example, solid waste production. The main categories of solid waste generated in the sewage treatment process are scum, screening material, grit and sludge (Andreoli et al., 2007). The amount of waste generated and its composition varies according to several factors including the sewage collection system, the characteristics of the population served, the presence of lift stations before the works, and the treatment processes used (Lins, 2010; Sperling, 2005).

In the preliminary units of treatment, significant amounts of oils, greases, coarse solids and grit are generated, which are generally disposed of in landfills, without concern in some developing countries such as Brazil about their proper disposal and their impact on the environment. Despite the low importance given, these wastes are considered one of the main management challenges in treatment plants in relation to their handling, treatment and final destination (Borges et al., 2015). However, the production of sludge varies according to the type of treatment adopted, and anaerobic processes generally produce smaller amounts of sludge. These residues contain pathogenic microorganisms, organic pollutants and heavy metals (Shiu et al., 2017), and require treatment and an adequate final destination. Soil pollution is a consequence that may occur through the disposal of sewage sludge containing heavy metals and pathogenic microorganisms (Lins, 2010).

Besides solid waste generation, there are impacts associated to the effluent quality. Insufficiently treated wastewater may cause silting and eutrophication, and it may contain micro-pollutants, such as pharmaceutical residues and endocrine disrupters, which are generally not removed by conventional treatment processes, requiring more advanced processes (Brandt et al., 2013).

Another impact that can be caused by wastewater treatment plants is atmospheric pollution via gaseous emissions (e.g., CH_4, CO_2, H_2S and N_2O) generated during wastewater treatment (Bani Shahabadi et al., 2010). In addition, the occurrence of odour might be a challenge as well (Lins, 2010).

Currently, two main strategies have been adopted to improve the sustainability of treatment plants: improving energy efficiency and resource recovery (Mo and Zhang, 2013). For this, an adequate planning in its design (choosing which process to implement) and operation becomes necessary. Plant managers could evaluate possible economic functions and uses of by-products before considering options for their treatment and final disposal. In addition to plan and to build new works that include resource recovery strategies, another alternative is the retrofitting of existing ones, which were initially designed to remove organic matter and nutrients instead of recovering them, making this option a major challenge (Bertanza et al., 2018). However, the inclusion of resource recovery strategies from sewage and sewage sludge at these stations allows for better environmental performance, reducing its impacts, and enabling the transition from a conventional view of linear economy towards circular economy (Venkata Mohan et al., 2016).

4. From waste to resource: a new paradigm in wastewater treatment systems

The concept of ecological sanitation (or abbreviated eco-san) emerged in the 1990s (Esrey et al., 1998). In 2001, the United Nations issued a publication entitled “Closing the loop: Ecological Sanitation for food security" to encourage closing the cycle in wastewater and sanitation management (Esrey et al., 2001). From then on, international events were held on the theme. In 2003, the International Water Association (IWA) created the Eco-Sanitation Specialist Group to replace the Sustainable Sanitation Group, and later on, this group was renamed to Resource-Oriented Sanitation Group (Hu et al., 2016).

Resource-oriented sanitation focuses on resource recovery, mainly from source separation (in decentralized systems), prioritizing water reuse, energy recovery, and the recycling of sewage constituents (Morandi et al., 2018; Simha et al., 2017). This new approach of resource-oriented sanitation seeks a more sustainable way of sanitation, with lower costs and low resource consumption such as water and energy (Ushijima et al., 2015). The sewage treatment is considered part of an integrated management of water resources, prioritizing the recovery of water, nutrients and energy (Andersson et al., 2018; Casiano Flores et al., 2018).

The term resource recovery has been addressed for decades (Miller, 1973; Verstraete et al., 2009). However, since the 21st century, with an increase in awareness of scarcity of resources, this approach has been gaining greater prominence in discussions, aiming to reinforce the resource recovery potential of wastewater treatment (Coats and Wilson, 2017; Tchobanoglous et al., 2015).

The concept of bio-refinery conceives the waste that is devalued as potential renewable resources, and which could be valued by the market (Venkata Mohan et al., 2016). The resource recovery approach represents a change in vision from the conventional treatment works towards a bio-refinery. Thus, the recovery of added-value products such as energy, nutrients and reclaimed water can be integrated into the plant by combining several practices to achieve maximum resource recovery (Mo and Zhang, 2013).

Thus, under the concept of sustainable development, domestic or municipal sewage is no longer considered a waste but a combination of resources. Based on this new understanding of effluents, it becomes necessary to discuss the challenges and opportunities that will become increasingly important in the near future (Tchobanoglous et al., 2015). The current challenge of achieving sustainable sanitation includes upgrading conventional wastewater treatment systems with recovery of renewable resources and energy efficiency upgrades, adopting a new sanitation paradigm considering decentralized systems and separation at source, and exploring the existing barriers to adaptation or modification of sewage treatment systems (Brands, 2014).

Among the resources present in sewage are nutrients (e.g., nitrogen and phosphorus), bioenergy, organic matter, reclaimed water of various qualities, alginate and metals. Thus, recovered resources can be defined as any material produced or extracted from the operations of wastewater treatment plants (Shore, 2017).

The recovery of resources can be undertaken in two ways: (a) after separation at source when each fraction of wastewater is separately collected of a household or building and each one will receive a different treatment; or (b) from sewage already collected (without segregation) for centralized or decentralized treatment. It is worth noting that both the segregation systems at source and the conventional treatment systems present significant opportunities and challenges in achieving sustainable sanitation (Brands, 2014; Krause and Rotter, 2017; Verstraete et al., 2009). However, systems that allow for the separation of wastewater at source maintain nutrients and organic matter in higher concentrations, which facilitates the treatment and recovery of resources (Verstraete et al., 2009).

The focus of this review is on resource recovery in wastewater treatment units. Fig. 1 illustrates two approaches: dissipative treatment and resource recovery. Concerning dissipative treatment, the waste generated during the treatment processes is not used and the treated effluent is discharged to the environment. In contrast, in resource-oriented sanitation systems, the by-products generated are sources for energy, materials recovery and reuse. According to Verstraete and

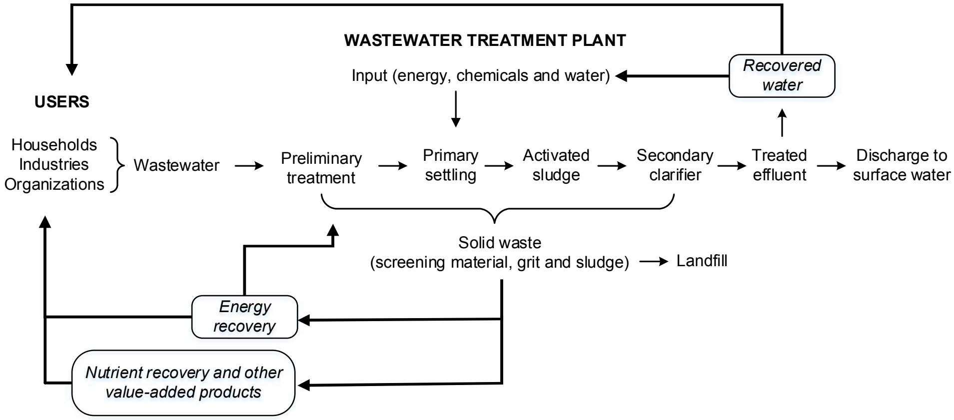

Fig. 1. Major pathways in wastewater treatment in cities, where thin arrows indicate dissipative treatment, and wide arrows and italic font highlight resource recovery integrated in wastewater treatment.

Vlaeminck (2011), in the model of the city of the future, the integrated water-materials-energy approach prioritizes the recovery of energy, nutrients and water, whereas in the predominant approach in the cities of the present, there are few such actions of recovery. Tchobanoglous et al. (2015) state that recovery of energy, nutrients and drinking water will become an important focus in future treatment plant projects.

In this context, the main factors that led to the recovery of resources (mainly nutrients and energy) from sewage are the value and limited availability of phosphorus, nitrogen and potassium as well as the increase in energy costs (Batstone et al., 2015; Sarvajayakesavalu et al., 2018). Other factors that led to the emergence of wastewater treatment processes with resource recovery are business opportunities, regulatory frameworks for environmental protection and the scarcity of natural resources (Andersson et al., 2016).

According to Verstraete and Vlaeminck (2011), the conventional system of wastewater treatment must be completely redesigned. In this sense, the recovery of resources generates a change in the planning of treatment plants that are designed to produce reclaimed water (for specific purposes) and to allow for the recovery of nutrients and energy (Batstone et al., 2015). The combination of conventional treatment technologies with energy and material recovery solutions has the potential to improve the sustainability of wastewater treatment works and reduce its costs (Puchongkawarin et al., 2015). In developing countries, some objectives for phosphorus recovery integration in existing sanitation systems are to increase wastewater collection, to develop a sustainable strategy for a long-term perspective in P-recovery, to build up the legal framework governing recycling and the market for fertilizers, to develop the business models for companies utilizing P streams from wastewater, and to encourage the research and development of new treatment technologies for P-rich wastewater (Zhou et al., 2017).

Until recently, resource recovery activities from wastewater predominantly focused on sludge and by-products of treatment (e.g., mesophilic anaerobic digestion of primary and secondary sludges and activated sludge for methane production and energy generation). Due to the fact that they are more concentrated, it allows for the recovery of resources (nutrients and energy) with few changes in the existing wastewater treatment plant (Puchongkawarin et al., 2015). However, currently there are several possibilities that have been analysed and technologies to generate numerous valuable products such as phosphorus as outlined in section 5.2.1.

5. Phosphorus recovery from wastewater

5.1. Motivations

The recovery of phosphorus from wastewater and sewage sludge is particularly important for many sectors of the economy (Lipińska, 2018). In 2014, the primary element phosphorus was declared as a critical raw material by the European Union (Blankesteijn, 2019).

Among the reasons for recovering nutrients from wastewater are the limited availability of fertilizers (particularly phosphorus), the challenges and associated costs of nitrogen and phosphorus removal in treatment systems to meet the limits of discharge of treated effluents that have become more restrictive, and the reduction of eutrophication in water bodies (Bashar et al., 2018; Mehta et al., 2015). The increasing cost of phosphate-based fertilizers is considered another important driver (Sarvajayakesavalu et al., 2018).

In this context, Puchongkawarin et al. (2015) argue that the increasing market value of sewage components such as ammonia and phosphorus is a key factor that positively influences the recovery of resources from wastewater. In addition, other drivers for phosphorus recovery are the reduction of maintenance costs of wastewater treatment works, and more specifically for phosphorus recovery from the ash of sewage sludge, the rather low organic concentration in the recovered product. From the perspective of fertilizer companies and the implementation for water boards, another motivation for phosphorus recovery is the sustainability label as a green marketing tool (De Boer et al., 2018).

5.2. Overview of processes for phosphorus recovery

There are several possible techniques for nutrient recovery and the processes can be classified as chemical, physical and biological (Venkata Mohan et al., 2016). Crystallization of struvite (magnesium ammonium phosphate) is a process for the simultaneous recovery of nitrogen and phosphorus. Struvite is a white crystal that contains essential nutrients for plant growth and can be applied directly to the soil. It is considered an excellent fertilizer, because it minimizes the loss of nutrients due to its slow release rate and its low water solubility. The concentration of magnesium and the pH of the medium are limiting factors for crystal formation (Hu et al., 2016). This technique of struvite crystallization can also be applied to the anaerobic digestion of sludge due to the high concentration of inorganic phosphorus and ammonia in reactors where this type of treatment occurs (Ahmed et al., 2015). Equation (1) presents the generic reaction of struvite formation (Doyle and Parsons, 2002):

$$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_46(H_2O) \quad (1)$$

where Mg^{2+} symbolises a magnesium cation, NH_4^+ represents an ammonium cation, PO_4^{3-} is a phosphate anion, H_2O is dihydrogen oxide, and $MgNH_4PO_46(H_2O)$ represents struvite.

The chemical precipitation of struvite can remove between 80 and 90% of the soluble phosphates and 20–30% of the soluble ammonia in the effluent (Le Corre et al., 2009). The main challenge in relation to struvite precipitation is the recovery of phosphorus from wastewater, if the phosphorus concentration is less than 50 mg/L (Mehta et al., 2015; Wong et al., 2013) and the concentration of suspended solids is above 2000 mg/L (Drechsel et al., 2015; Mehta et al., 2015). So, one possibility is to apply the struvite precipitation technique for secondary streams (such as generated in primary sludge thickening or after dewatering of the digested sludge) that have higher phosphorus concentrations.

As for nitrogen recovery, only about 10% of available nitrogen (after anaerobic digestion) can be removed by precipitation of struvite (Batstone et al., 2015). The most common method used for the recovery of phosphate and ammonia involves the formation of struvite crystals in an upward flow fluidized bed reactor. In this reactor, the formation of the crystals is accelerated by the addition of excess Mg^{2+}, which is added to the sewage at elevated pH and temperature (Tchobanoglous et al., 2015).

One of the advantages of struvite precipitation is that it reduces transport costs of the fertilizer. However, some challenges of struvite crystallization are the low-value products with overweighing cost, complex operating conditions and low recovery efficacy (Wu et al., 2019). (Ahmed et al., 2015).

Chemical precipitation of phosphorus can also occur with the addition of calcium (Ca^{2+}, very common), aluminium (Al^{3+}) or iron (Fe^{3+}). The application of iron and aluminium is less usual, since aluminium (in elevated concentrations) is toxic to most plants and iron is strongly bound to phosphorus, making it less bioavailable. One innovative method that has gained attention is phosphorus recovery as vivianite (predominant in digested sludge) (Wilfert et al., 2018). The advantages of this process are its natural ubiquity, easy accessibility and foreseeable economic value, but its current development stage is at its infancy and further studies are required; for instance, on how to separate vivianite from the sewage sludge to achieve higher phosphate recovery efficiencies (Wilfert et al., 2018; Wu et al., 2019).

There are also physical recovery processes based on ion exchange, adsorption and membrane systems that are being used to recover nutrients from wastewater. One of its applications is the recovery of ammonia, nitrate or phosphates for the treatment of secondary effluent through adsorption by ion exchange. Johir et al. (2011) investigated a membrane bioreactor (MBR) with ion-exchange as post-treatment for organic removal and nutrient recovery and showed that the ion-exchange process effectively removed the nutrients from the effluent of the MBR. Ion exchange presents the advantage of operating over a wide temperature range, which is still a limitation in biological removal processes. On the other hand, there are challenges to be considered such as the high investment cost, the limited capacity of the adsorbents and the addition of chemicals for adsorbent regeneration (Miladinovic and Weatherley, 2008; Puchongkawarin et al., 2015).

Membrane filtration systems, however, generate a concentrate (including nitrogen, phosphorus and potassium) that may be suitable for use in irrigation or in subsequent nutrient recovery processes. The disadvantages associated with these systems are the high energy consumption and the accumulation of contaminants and salts in the membranes, which is a process called fouling (Mehta et al., 2015).

Another possible physical process is to add urine or wastewater to natural zeolites such as clinoptilolite (Mehta et al., 2015). Due to their high cation-exchange ability, especially for potassium and ammonium, zeolites have been used as adsorbent in separation and purification processes (Kocatürk-Schumacher et al., 2017). Through ionic exchange, ammonium is transferred to the mineral, and after that, it is possible to use the final product (nutrient enriched clinoptilolite) as slow release fertilizer and soil conditioner in plant cultivation (Beler-Baykal et al., 2011). One application of the ion exchange with zeolites is for the treatment of digestate (concentrated valuable nutrients) in wastewater treatment (Kocatürk-Schumacher et al., 2017).

The use of constructed wetlands can be considered an example of biological assimilation of nutrients present in the wastewater. The assimilation is done by, for example, the plants or algae present in the wetlands, which besides promoting the treatment of the effluent will result in biomass rich in protein (Venkata Mohan et al., 2016). Macrophytes have a high ability to accumulate nutrients in the rhizomes and are rooted in the filter media or the free water column. In addition, biofilms adhering to the rhizosphere assist in the removal of phosphorus (31–71%) (Ahmed et al., 2015; Mehta et al., 2015). The nutrient retention efficiency for plant accumulation varies according to plant species, effluent characteristics, wetland type and environmental conditions (e.g., temperature). After harvesting, wetland plants can be used as an animal feed, as fertilizers or to be processed through specific technologies for the release of nutrients (e.g., anaerobic digestion of biomass for biogas production) (Mehta et al., 2015).

Also, in this context, it is possible to recover nutrients from sewage with the production of biomass (e.g., microalgae cultivation) during the treatment, which can also be used as an energy source (Andersson et al., 2016). In wastewater treatment, microalgae may contribute to the absorption of organic matter, inorganic matter and nutrients (Mo and Zhang, 2013). Some studies have evaluated the recovery of nitrogen present in the domestic sewage through the growth of aquatic plants for biomass production in, for example, ponds). Algae cultivation can also occur within the secondary effluent stream from the anaerobic digester (nutrient-rich) instead of recirculating it to the beginning of the treatment train. This stream can be treated through a lagoon process for cultivation of biomass; or by adding a biomass culture to the post-treatment of the secondary effluent (Dalrymple et al., 2013). The advantages of biomass production (for nutrient recovery) are a rapid algal growth rate and a low area demand compared to higher plants as well as a low hydraulic retention time (Ahmed et al., 2015; Mehta et al., 2015). It is worth mentioning that the recovery efficiency depends on the biomass growth potential.

In addition to nutrient recovery processes, there are nutrient accumulation techniques, which are necessary when the effluent has a low concentration of nutrients (< 20 mg/L) and a high flow rate. For example, to recover soluble nutrients in domestic wastewater, the use of accumulation techniques is recommended, as it usually has a low concentration of phosphorus (6–8 mg/L). The accumulation of nutrients can occur through plants, microorganisms and physicochemical mechanisms (e.g., chemical precipitation or separation by membranes). After accumulation, other technologies can be applied to allow for recovery or reuse. Thus, after accumulation and/or uptake, a nutrient release technique can be applied, which can be based on biochemical processes such as anaerobic digestion. After this liberation step, nutrient extraction can occur through different technologies such as crystallization and electro-dialysis. By using accumulation, release and extraction steps, the nutrient recovery efficiency can be improved (Batstone et al., 2015; Mehta et al., 2015).

Usually, in wastewater treatment plants, physical treatment (pretreatment and primary treatment) is initially carried out, followed by biological treatment, where the phosphorus is released from the degradation of organic molecules. Several types of phosphorus removal technologies exist to treat wastewater and commonly used methods are Bio-P removal or phosphorus removal via chemical dosing. Phosphorus recovery processes could be combined to the existing processes. It is

Table 1
Characteristics of some technologies for phosphorus recovery from the liquid phase in wastewater treatment.

Technology or process	Treatment units or technical principle	Scale or status	Source	Phosphorus influent[b] (mg/L)	Recovered product	Phosphorus recovery (%)[c]	Reference	Location of installation[d]
Ostara Pearl	Crystallization	Full-scale	Digester supernatant; thickening supernatant; dewatering liquor	100-900 PO_4-P	Struvite	10 to 30	Amann et al. (2018); Egle et al. (2016); Kabbe (2017) Nieminen (2010)	USA; England; Canada; The Netherlands; Spain
P-Roc	Crystallization; stirring reactor using CSH as an adsorbent; batch modus	n.f.	Digester supernatant	n.f.	CaP; struvite	10 to 30	Cornel and Schaum (2009); Egle et al. (2016); Sartorius et al. (2012)	Germany
DHV Crystallactor	Crystallization of metal salts; dosing of lime or magnesium hydroxide, or a combination of caustic soda and magnesium chloride as reagents; after atmospheric drying, pellets are obtained	Full-scale	Digester supernatant	PO_4-P > 25 mg/L	CaP; magnesium phosphate or struvite pellets	10 to 40	Cornel and Schaum (2009); Egle et al. (2016); Kabbe (2017)	China; Germany
Multiform Harvest	Crystallization; dissolved phosphorus and ammonia combine with magnesium chloride and quickly crystallize into struvite	Full-scale	Digester supernatant and dewatering liquor	n.f.	Struvite	80[e]	Kabbe (2017); Kataki et al. (2016)	USA
Phosphogreen	Precipitation; crystallization	Full-scale	Dewatering liquor	70	Struvite	Up to 90%[e]	Kabbe (2017); Suez (2018)	Denmark; France
Struvia	Crystallization; advanced lamellar clarification	Full-scale	Sludge dewatering liquor; digester supernatant	PO_4-P > 50	Struvite, CaP	n.f.	Kabbe (2017); Kleemann (2015)	Denmark
ANPHOS	Crystallization; aeration of wastewater, which induces a positive pH shift; addition of magnesium (hydr)oxide to form MgAP or MgKP, after the struvite is precipitated, dewatered and dried	Full-scale	Digester supernatant	> 50	Struvite	80–90[e]	Desmidt et al. (2015); Kabbe (2017)	The Netherlands
PRISA	Precipitation; crystallization	Pilot plant	Digester supernatant	n.f.	Struvite	10 a 25	Egle et al. (2016)	Germany
Air Prex	Precipitation; crystallization	Full-scale	Digested sludge before dewatering; sludge liquor	150–250	Struvite	10 a 25	Desmidt et al. (2015); Kabbe (2017); Kataki et al. (2016)	Germany; The Netherlands; China
PHOSPAQ	Addition of magnesium oxide; the struvite is retained by separators, followed by a screw press and are transferred into a container	Full-scale	Sludge dewatering liquor; digester supernatant	50 < PO_4-P < 65	Struvite	70–95[e]	Desmidt et al. (2015); Kabbe (2017); Ye et al. (2017)	The Netherlands; England
PhosNix	Struvite reactor with addition of Mg $(OH)_2$ and NaOH; screen separator.	Full-scale	Sludge dewatering liquor; wastewater after digestion	100–150 mg/L PO_4-P	Struvite	80–90[e]	Desmidt et al. (2015); Nieminen (2010).	Japan
REM-NUT	Ion exchange. In the columns, ammonium ions are exchanged for sodium ions, and phosphate is exchanged for chloride ions; regeneration with sodium chloride. Magnesium chloride and sodium hydroxide addition for precipitation.	Pilot plant	Secondary effluent	n.f.	Struvite; CaP	45–60	Amann et al., (2018); Levlin (2001)	Italy
Microalgae production (hybrid photobioreactors)	Homogenization tanks; hybrid photobioreactors; storage tanks; settler; solar disinfection; adsorption column	Pilot scale/ experimental plant	Agricultural runoff; urban wastewater	PO_3^{4} 0.8 ± 1.1	Liquid fertilizer for irrigation	77.8–408.7 mg/L of P Total in the digestate	Uggetti et al. (2018)	Spain

(*continued on next page*)

Table 1 (*continued*)

Osmotic membrane bioreactor + precipitation	Clear supernatant was withdrawn weekly from the bioreactor after settling; as part of the CO_2 stripping method, $NaHCO_3$ was added to the supernatant; CO_2 stripping was carried out at a constant air flow rate	Laboratory scale	Bioreactor (P-rich) supernatant	7.1 mg/L PO_4-P influent of OMBR, and 3483.5 accumulative PO_4-P	ACP	50 overall efficiency of phosphorus recovery in the process; > 95% PO_4-P recovery via ACP precipitation	Qiu and Ting (2014)	Germany

CaP = calcium phosphate; CSH = calcium silicate hydrate; PO4-P = ortho-phosphate-phosphorus; MgAP = magnesium-ammonium-phosphate; MgKP = magnesium-potassium-phosphate; ACP = amorphous calcium phosphate; OMBR = osmotic membrane bioreactor; n.f. = not found; [a] Based on Egle et al. (2016), the aqueous phase includes secondary treated effluent, sewage, digested sludge and digester supernatant; [b] "influent" means the source (described in the previous column); [c] in % of the WWTP influent; [d] country where there is a wastewater treatment plant with a phosphorus recovery process; [e] removal efficiency in relation to the input and output of the recovery process.

worth mentioning that currently, the most used and recommended method in the literature for phosphorus recovery from wastewater treatment is through struvite ($NH_4MgPO_4.6H_2O$) precipitation, as it has a low risk of contamination by pathogens and is a product that can be easily transported (Batstone et al., 2015; Desmidt et al., 2015; Mehta et al., 2015).

5.2.1. Assessment of technologies for phosphorus recovery from liquid and solid phases of wastewater

Recovery processes precede recycling of phosphorus and create intermediates (recyclates), which are raw material for subsequent processes to generate products (e.g., calcium phosphate or struvite). Most of the phosphorus recovery and recycling technologies from wastewater and sewage sludge ash aim to recover phosphorus in mineral form. Another option is conventional phosphorus recycling through the recycling of organic phosphorus such as direct application of sewage sludge in agriculture or for composting purposes (Hukari et al., 2016).

The recovery of phosphorus present in wastewater treatment plants can take place from the liquid phase (i.e. the effluent from a treatment unit such as the supernatant from a digester), sludge or ashes (originated after sludge incineration), and represents a promising alternative mainly in relation to the recovery from the solid phase, as these residues (sludge and ash) contain high concentrations of phosphorus. Currently, most technologies for phosphorus recovery are focused on sludge or ash according to Desmidt et al. (2015). The rate of recovery of phosphorus in the liquid phase may reach 50–60%, while the recovery rate of phosphorus from sludge and its ashes can reach 90% (Cornel and Schaum, 2009). Tables 1–3 summarise some of the phosphorus recovery technologies from the liquid and solid phases.

The liquid streams generated in the primary and secondary sludge dewatering processes combined or digested contain high concentrations of nutrients (ammonia and ortho-phosphate). Therefore, the phosphorus present in the secondary streams (generated in primary sludge thickening or the excess activated sludge process as well as after dewatering of the digested sludge) can be recovered and recycled as fertilizer, and the recovery of nutrients from these recirculation streams of the processes are economically feasible (Tchobanoglous et al., 2015). The main products that can be recovered from secondary streams containing phosphorus and ammonia include struvite, calcium phosphate, ammonium sulphate and ammonium nitrate. Some of the processes that allow for the recovery from secondary currents are AirPrex®, Crystalactor®, Pearl®, PhosNix® and PHOSPAQ® (Khiewwijit et al., 2015; Tchobanoglous et al., 2015).

With the removal of phosphorus by the treatment system, about 90% of it is transferred to the sludge. Recovery in the liquid phase includes slow crystallization (DHV Crystalactor®, Ostara® and P-RoC®) and instant precipitation (PRISA) processes, which can recover 85–90% of the phosphorus dissolved in the supernatant. As there are low concentrations of heavy metals in the supernatant of the digester, there is low transfer to the soil, if there is an application of this product (fertilizer) in agriculture (Egle et al., 2016).

Ostara's Pearl® is a reactor for treatment of sludge after anaerobic digestion. The corresponding crystallization process extracts about 85% of the phosphates in the form of 1650 kg/day of high-quality struvite, when it operates at its maximum treatment capacity (416 m^3/day). The struvite is subsequently processed and sold (Sikosana et al., 2017). The Netherlands also recover struvite from digested sludge, based on a process adding magnesium chloride, and aeration for pH increase (Leeuwen et al., 2018; Van Der Hoek et al., 2017).

In addition, it is possible to recover phosphorus from the digested sludge before dewatering (Desmidt et al., 2015). For example, struvite can be precipitated in the sludge through acid leaching and subsequent chemical precipitation of phosphorus (Remy et al., 2016). As the concentrations of heavy metals present in the sludge or its ash are greater than the concentrations in the liquid phase, processes for decontamination need to be applied in such cases. Chemical extraction processes

Table 2
Characteristics of some technologies for phosphorus recovery from the sewage sludge phase in wastewater treatment.

Technology or process	Treatment units or technical principle	Scale or status	Source	Phosphorus influent[b] (mg/L)	Recovered product	Phosphorus recovery (%)[c]	Reference	Location of installation[d]
Gifhorn	Wet chemical extraction; sulfidic precipitation of interfering ions; precipitation	Full-scale	Thickened sludge; dewatered sludge; digested sludge	n.f.	Struvite; CaP; FeP	35–60	Amann et al. (2018); Egle et al. (2016); Kabbe (2017)	Germany
Stuttgart	Wet chemical extraction; complexation of interfering ions; precipitation	Demo; pilot-plant	Digested sludge	n.f.	Struvite; CaP; FeP	35–60	Amann et al. (2018); Egle et al. (2016); Kabbe (2017)	Germany
Budenheim and Extraphos	Wet chemical leaching; carbon dioxide extraction; solid/liquid separation; phosphate precipitation	Pilot-plant	Digested sludge	n.f.	Dicalcium phosphate	40–60	Egle et al. (2016); Günther et al. (2018); Kabbe (2017)	Germany
Aqua Reci	Super critical water oxidation; acid/alkaline leaching; precipitation	Full-scale	Digested sludge; thickened sludge; dewatered sludge	n.f.	CaP; FeP; AlP	40–60	Amann et al. (2018); Egle et al. (2016); Sartorius et al. (2012); Stendahl and Jäfverström (2004)	Sweden
LOPROX/ PHOXNAM	Combination of low-pressure wet oxidation and nanofiltration; acid and hydrothermal digestion for heavy metal separation	Full-scale, pilot-plant	Thickened sludge	n.f.	Struvite, phosphoric acid	40–50	Amann et al. (2018); Egle et al. (2016); Sartorius et al. (2012)	n.f.
MEPHREC	Metallurgic melt-gassing; process charged with briquettes from dewatered sludge; briquettes are dried; preheated air and oxygen are injected to the smelting zone; production of P-rich slag	Pilot-plant	Dewatered sludge	n.f.	P-rich slag	65–70	Amann et al. (2018); Egle et al. (2016); Günther et al. (2018); Rapf and Raupenstrauch (2012); Sartorius et al. (2012)	Germany
NuReSys	Stripper for pH control; stirred tank reactor; $MgCl_2$ addition to promote active struvite formation	Full-scale	Digested sludge; thickened sludge	60–150	Struvite	80[e] of PO_4-P removal in the digested sludge; recovery of 15% of the total P load of the plant at Leuven, Belgium	Desmidt et al. (2015); Günther et al. (2018); Kabbe (2017); Marchi et al. (2015)Ye et al. (2017)	Germany; Belgium; The Netherlands
Seaborne	Wet chemical leaching; sulphuric acid added to sludge; dewatered sludge incineration; magnesium hydroxide and sodium hydroxide solution is added for precipitation	Full-scale	Digested sludge	600 P total	Struvite; Ca/ Mg-P	90[e]	Cornel and Schaum (2009); Desmidt et al. (2015); Günther et al. (2018); Nieminem (2010); Sartorius et al. (2012).	Germany

PO_4-P = ortho-phosphate-phosphorus; CaP = calcium phosphate; FeP = iron phosphide; AlP = aluminium phosphide; $MgCl_2$ = magnesium chloride; Mg-P = magnesium phosphide; H_3PO_4 = phosphoric acid; MFC = microbial fuel cell; n.f. = not found; [a] Based on Egle et al. (2016) sewage sludge includes untreated sludge as well as thickened and dewatered sludge; [b] "influent" means the source (described in the previous column); [c] in % of the WWTP influent; [d] country where there is a wastewater treatment plant with a phosphorus recovery process; [e] removal efficiency is in relation to the input and output of the recovery process/reactor.

Table 3
Characteristics of some technologies for phosphorus recovery from mono-incinerated sewage sludge ashes.

Technology/ Process	Treatment units/Technical principle	Scale/Status	Source	Phosphorus concentration in influent[a]	Recovered product	Phosphorus recovery (%)	Reference	Location of instalations[d]
Ash2Phos	Wet chemical process; dissolution of sludge ashes into sulphuric acid or hydrochloric acid; precipitation to remove iron, phosphorus and aluminium	Pilot-plant	Sewage sludge ash	n.f.	Mono/dicalcium phosphate; Mono/di-ammonium phosphate	> 90[b]	Easy Mining (2019)	Sweden
EcoPhos	Acidic wet chemical; leaching; H_3PO_4 production; removal of heavy metals through ion exchange	Full-scale	Sewage sludge ash	n.f.	Dicalcium phosphate; Phosphoric acid	95[b]; 80-85[c]	Egle et al. (2016); Amann et al. (2018); Kabbe (2017)	Bulgaria; France
LeachPhos	Acidic wet chemical leaching	Pilot-plant	Sewage sludge ash	n.f.	CaP	65-70[c]; 70–80[b]	Amann et al. (2018); Egle et al. (2016)	Switzerland
SEPHOS	Wet chemical; sulphuric acid addition; increase of pH value in the filtrate; aluminium phosphate precipitation	Lab-scale	Sewage sludge ash	n.f.	$CaPO_4$; AlP; CaP	n.f.	Cornel and Schaum (2009); Nieminen (2010); Sartorius et al. (2012)	Germany
PASCH	Acidic wet-chemical, leaching; liquid-liquid removal of heavy metals	Pilot-plant; lab-scale	Sewage sludge ash	n.f.	CaP	65-70[c]; 70–80%[b]	Amann et al. (2018); Egle et al. (2016)	Switzerland
RecoPhos	Acidic wet chemical extraction	Pilot-plant	Sewage sludge ash	n.f.	Mineral fertilizer, H_3PO_4/ P4	85[c]; 100[b]	Egle et al. (2016); Amann et al. (2018)	Germany, Belgium, Austria
Termphos	Thermo-electrical	Industrial process	Sewage sludge ash	0.09 ton P/ton ash	P4 (elemental phosphorus)	85[c]; 95[b]	Amann et al. (2018); Desmidt et al. (2015); Egle et al. (2016); Sartorius et al. (2012)	The Netherlands
TetraPhos	Sewage sludge incineration; ashes are mixed with phosphoric acid, which is enriched with ash-bound phosphorus	Pilot-plant	Sewage sludge ash	n.f.	H_3PO_4	n.f.	Kabbe (2017); Remondis Aktuell (2014)	Germany
AshDec	Thermo-chemical; heavy metal depollution; Cl-source such as $MgCl_2$	Pilot-plant; semi-industrial	Sewage sludge ash	0.046 ton P/ton ash	Ash; CaNaPO4	85[c]; 98[b]	Amann et al. (2018); Desmidt et al. (2015); Egle et al. (2016); Sartorius et al. (2012)	Austria

H_3PO_4 = phosphoric acid; CaP = calcium phosphate; $CaPO_4$ = calcium ortho-phosphate; AlP = aluminium phosphide; P4 = elemental phosphorus; $CaNaPO_4$ = calcium sodium phosphate; Cl = chlorine; $MgCl_2$ = magnesium chloride; n.f. = not found; [a] "influent" means sewage sludge ash; [b] recovery rate of phosphorus from the ash input; [c] from the influent of a wastewater treatment plant; [d] country where there is a wastewater treatment plant with a phosphorus recovery process.

(Stuttgart, Gifhorn and Budenheim® processes) and oxidation (LOPROX® and Aqua Reci®) show a high removal potential (up to 98% for all heavy metals considering As, Cd, Cs, Cu, Hg, Ni, Pb and Zn) for sewage sludge. Therefore, the transfer of heavy metals to the recovered product and consequently to agriculture is considered low. The potential of phosphorus recovery of these processes (Stuttgart, Gifhorn, Budenheim®, LOPROX® and Aqua Reci®) is 45–65% of the phosphorus present in the sludge and 40–60% of the phosphorus available in raw wastewater (Egle et al., 2016).

In relation to recovery from the incinerated sludge ash, there are two main methods of phosphorus recovery: dry thermal and wet chemical. In the former, the phosphorus is recovered by dissolution of ashes, and in the later, phosphorus is extracted by the addition of an organic acid or solvent and subsequently recovered from that solution (Desmidt et al., 2015; Kaikake et al., 2009). Egle et al. (2016) concluded that the EcoPhos® process allows for a recovery of up to 80% of the phosphorus entering the wastewater treatment plant and the AshDec® process allows for a recovery rate of 85%. As for the concentration of heavy metals, high rates (above 98%) were obtained for the removal of some heavy metals with the AshDec® process. Cd, Cu, Pb and Zn could be reduced by up to 90%, while As, Cr and Ni remained in the ashes in high percentages (Egle et al., 2016).

Wang et al. (2018a) assessed a new process for phosphorus recovery involving struvite from sewage sludge ash. The process transforms P to amorphous iron phosphate (Fe-P) and aluminium phosphate (Al-P) by acid washing followed by alkali precipitation, re-dissolution of Fe-P and Al-P via acid washing and adsorption of Fe and Al ions by cation exchange resin, and struvite crystallization. Their results were promising, indicating that over 99% of phosphorus in the purified P solution was recovered as struvite (with high purity and low heavy metals contents).

The recovery rates are higher for technologies concerned with sewage sludge ashes in comparison to the ones from sewage sludge and the liquid phase. However, it requires the incineration of sewage sludge to produce ashes, which are the sources for phosphorus recovery. There are impacts associated with incineration of sewage sludge such as difficulty for centralization and the high cost of incineration equipment. Such technologies are considered economically viable only in large wastewater treatment plants, mainly because of the need for large investment associated with building a facility to meet environmental criteria (Cieślik Konieczka, 2017). De Boer et al. (2018) mention as a viable possibility an incineration partnership with water boards for producing sewage sludge ashes. However, for small plants, this could be more difficult.

Phosphorus recovery technology implementations at wastewater treatment works are not common (De Boer et al., 2018). Tables 1–3 indicate that phosphorus recovery selected technologies has been implemented in developed countries with the exception of China, which is classified as a developing economy, considering the classification from UNCTAD (2018). Therefore, there is an opportunity to increase the implementation of phosphorus recovery technologies from wastewater in large cities in developing countries.

The situation in China can be mentioned as an example for illustrative purposes. Organics and nutrient recovery from wastewater and sludge is likely to be improved significantly (Sun et al., 2016). Zhou et al. (2017) conducted a systematic analysis of different options of phosphorus recovery based on real operational data (concentrations of phosphorus in sludge water, supernatants and concentrates, iron and aluminium in sludge and sludge ashes) from some wastewater treatment plants (WWTP) in China. One of the proposed P recovery technologies was AirPrex from digested sludge. Among the plants with sewage sludge digestion, most of them have reported that struvite precipitation in pipes and dewatering facilities has been a problematic issue. For most of these plants using anaerobic digestion, land application or agricultural use is the first choice for sewage disposal. For the P that is fixed within the sludge, after chemical precipitation with ferrous or ferric salts or aluminum, direct struvite crystallization is not a suitable option for recovery. Hence, with the current sewage and wastewater treatment facilities in China, only a few WWTP are adapted to this option. In the Tianjing Chennan sludge treatment plant, a new project with recovery of phosphate from sludge water (digester supernatant) with the AirPrex® process is under construction. Regarding the processes of P recovery from sludge water with sludge extraction (e.g., Gifhorn, Stuttgart and Budenheim), these processes are technically suitable for digested sludge from plants with both enhanced biological P removal and chemical P elimination. The option of phosphorus recovery from sewage sludge ashes is still limited, because only about 3.45% of sludge in China is treated by incineration due to the low P concentration in sludge ash. The recovery from industrial wastewater with a high concentration of P shows higher potential than in municipal WWTP due to easier market access and benefits to its operators (Zhou et al., 2017).

Even in developing world cities where there is sewage collection, few of them have wastewater treatment facilities (Mihelcic et al., 2011). In sub-Saharan Africa as well as parts of Asia and Central and South America, wastewater treatment systems, when they exist, are commonly minimum requirement systems and do often not function properly. In Mexico and many countries of South America, wastewater treatment has advanced, but wastewater sludge and biosolids management has only recently been considered as important. Advanced regulatory structures have to be created to facilitate the implementation of nutrient recovery strategies from wastewater treatment (UN-Habitat, 2008).

Mihelcic et al. (2011) quantified the mass of total phosphorus present in human excreta (urine and faeces) for the year 2009 and provided an estimate for 2050, globally, regionally and per specific countries. The figures are higher in urban areas than in rural ones due to anticipated population growth. Regarding developing countries, the greatest potential to implement nutrient recovery strategies is in Africa and Asia (especially Eastern Asia, Southern Asia and Sub-Saharan regions). Such solutions may comprise source separation systems, composting of faeces and biosolids recovery via new and existing technologies.

This review focuses on phosphorus recovery and recycling technologies from wastewater and sewage sludge ash to recover phosphorus in mineral form. However, there is also the option of conventional P recycling, which is practiced in some developing countries. For example, in Egypt, the use of dry sludge in agriculture is a practice that has a wide and a good market nationally. In 2007, about 0.66 million tons of the dried sewage sludge have been sold to farmers, which is equivalent to more than 85% of the total produced sewage sludge from all wastewater treatment works in the country (Ghazy et al., 2009).

Other developing countries and emerging economies such as Brazil, Chile, China (Chen et al., 2012; Zhou et al., 2017), Colombia, Ghana, India, Indonesia, Mexico, Philippines, Uganda and Vietnam reuse sewage (either raw or composted) as a source of organic matter and nutrients for fertilizer and soil amendment products (UN-Habitat, 2008). However, with the increasing demand in production of sewage sludge, it is necessary to develop more efficient and more sustainable technologies to ensure a safe and suitable reuse of sludge (Ghazy et al., 2009).

Simple and low-cost technologies for sanitation focusing on nutrient recovery in less developed economies have been reported elsewhere and most of them are based on the principles of source-separation systems. Nutrients (N, P and K) from urine are recovered by affordable technologies such as urine-diverting dehydration toilets, followed by struvite precipitation and nitrification and distillation, producing valuable fertilizer for local communities (Udert et al., 2015; Krähenbühl et al., 2016; Tilley, 2016). These source-separation solutions are feasible, especially for small towns and rural areas such as rural China (Xu et al., 2019). Krähenbühl et al. (2016) investigated struvite recovery from source-separate urine whether process requirements, costs and environmental impacts would make this process viable for magnesium production in decentralized settings in Nepal. Their results showed that using local magnesite would provide the cheapest source of magnesium. The cost of magnesium in low-income and in developing countries is crucial to the viability and implementation of struvite precipitation. Another project of low-cost nature was developed in Burkina Faso by Dakouré et al. (2017) with the implementation of composting toilets, greywater treatment facilities and urine collection at pilot scale in rural areas. However, the families stopped to use these technologies after the end of the project, especially due to lack of economic incentives.

In some contexts of developing countries, local governments concentrate efforts on sanitation services (mainly on wastewater treatment and expansion of sewerage networks) and give little priority to other related aspects such as sludge management (Ghazy et al., 2009), which may explain why phosphorus recovery technologies are not largely implemented. The challenge in these countries is to increase the basic sanitation coverage for the population and combining these wastewater treatment systems with nutrient recovery (Mihelcic et al., 2011). Less developed countries cannot afford the same level of urban sanitary infrastructure compared to wealthier countries. The latter employs long and complex sewage networks in cities as well as robust and efficient WWTP. However, developing countries will have to innovate and to reinvent solutions, maybe leapfrogging the conventional steps undertaken by the rich countries (Andersson et al., 2018). So, as the developing and low-income countries may not be able to adopt high-cost technologies, they should consider choosing simple and cost-effective methods (Sarvajayakesavalu et al., 2018). These solutions should have low costs, high recovery rates, no specialized labour requirement for operation and maintenance and no large space need. The latter is mainly important for large urban settlements.

5.2.2. Phosphorus recovery in developing countries: Latin America and the Caribbean region example

For countries located in the tropical humid areas of Central and South America, phosphorus deficiency is the major constraint to agricultural productivity. In this region, phosphate rocks for fertilizer production are of two major types-sedimentary deposits of phosphate rock formed in coastal marine or lacustrine environments, and phosphate deposits associated with alkaline and carbonatite igneous complexes. Some of these deposits are irregularly distributed and many are too small, located in mountainous terrain or lack adequate infrastructure areas (Appleton and Notholt, 2002). The phosphate fertilizer production is lower than the demand in Latin America and Caribbean (LAC) indicating that this is a very important resource, which is becoming scarce. Moreover, the trend is toward an increase in demand for the next years. The phosphate demand in LAC was 6620 thousand tonnes P_2O_5 in 2016 (FAO, 2017).

In this context, it is possible to make some recommendations regarding phosphorus recovery technologies that could be applied to the LAC region. They should be based on the predominant technologies in WWTP. Based on Noyola et al. (2012), the most used sewage treatment technologies in Latin American countries are stabilization ponds (38%), activated sludge (26%) and the upflow anaerobic sludge blanket reactors (17%) representing 81% of the treatment facilities. The highest treated flow per type of technology is linked to activated sludge technology. Regarding the size of the plants, 67% of the plants in the sample are small (flow < 25 L/s) and the very small facilities (influent flow < 5 L/s) are extensively applied in the region (34% of the sample), especially in Mexico and Brazil. Considering these characteristics, some scenarios for phosphorus recovery can be suggested. For activated sludge plants, one potential scenario could be the phosphorus recovery from liquid phase from sludge dewatering liquor (example of PHOSPAQ, Phosphogreen or Phosnix; Table 1). Alternatively, based on sewage sludge treatment that is adopted in the plant, other technologies for P recovery from sludge (Table 2) can be introduced. This is especially interesting for plants with activated sludge, which is a process that produces excess sludge that should be treated and managed. Another scenario, applicable for stabilization pond plants could be microalgae cultivation from the mainstream, which is interesting due to the favourable weather in these countries, although this technology is still at pilot scale.

There is a high potential for implementation of phosphorus recovery technologies in new WWTP, since the sanitation coverage should increase in LAC. Currently about 77% of the population in LAC lacks access to safe sanitation. Only an estimated 28% of the wastewater collected by public sewers receives adequate treatment before being discharged to the environment (Inter-American Development Bank, 2017).

5.2.3. Environmental impacts

In relation to the environmental impacts associated with the recovery of phosphorus from wastewater, Amann et al. (2018) compared different phosphorus recovery technologies with each other. They concluded that the recovery from the liquid phase generates less emissions and has lower energy demands, but is usually linked to low rates of recovery, while recovery technologies from sludge (solid phase) present comparatively higher emissions and higher demands for energy. The recovery of phosphorus from sludge ash is the most promising option, since it presents a higher recycling rate with the possibility of decontamination concerning heavy metals (Amann et al., 2018). However, phosphorus recovery processes based on sludge ash have a higher cost, mainly because they require a lot of energy for incineration (Drechsel et al., 2015).

In terms of cumulative energy demand, Amann et al. (2018) performed a life cycle analysis comparing different processes for phosphorus recovery and found that the processes Aquac Reci, PHOXNAN and Stuttgart (from sewage sludge) had the highest increases in energy consumption (423, 345 and 290%, respectively). The processes RecoPhos, Single Super Phosphate and Thermphos (from sludge ashes) had the lowest energy demands (−112, −39 and −38% in this order). The recovery potentials of these technologies (% of phosphorus in raw wastewater) are 60, 40–50 and 35–55, and 85% for the other three processes with lowest energy demand. Other than for sewage sludge, technologies that recover phosphorus from sewage sludge ashes show only a medium increase or even decrease in cumulative energy demand compared to the reference system comprising a wastewater treatment train with mono-incineration of sludge as well as disposal of all wastes.

Sikosana et al. (2017) compared the energy consumption of two designs for phosphorus precipitation from anaerobic digester liquor, considering a phosphorus concentration between 89 and 190 mg/L, magnesium (Mg) ranging from 29 to 67 mg/L and a design flow rate of approximately 1060 m^3/d. The technology studied was a crystallization fluidized bed reactor. The struvite was filtered and dried (92% dry solids). For a low-quality process, there was no recycling of reactor effluent and the collected struvite had dry solids of 20%. The results showed that the energy consumptions were: 727, 204 and 159 kWh/day for the high-grade struvite, low-grade struvite and phosphorus precipitation designs, respectively. So, implementing low-grade struvite treatment is a beneficial alternative to current methods from an environmental point of view, and low-grade struvite production was the cheapest option investigated (Sikosana et al., 2017).

Besides the energy demand, there are other impacts involved in the phosphorus recovery from wastewater, such as emissions to water, air and soil and consumption of reactants. Pradel and Aissani (2019) tried to estimate environmental impacts of sludge-based phosphate fertilizer production to evaluate if recovering phosphorus by producing sludge-based phosphate fertilizer could be a suitable alternative to producing mineral fertilizers from phosphate rocks. They quantified the inflows and outflows of the nitrogen, carbon and phosphorus and the system's inputs (consumption of energy, reactants and fuel) and outputs (emissions to air, water and soil). Four scenarios were compared with one reference scenario (Triple Superphosphate production). Results of this study indicated that sludge-based phosphate fertilizers appeared to have higher environmental impacts than mineral phosphate fertilizers production, mainly due to their consumption of large amounts of electricity and reactants needed to recover phosphorus, and their low phosphorus content in comparison with phosphate rocks. So, evaluating the environmental impacts associated with phosphorus recovery technologies should be an important aspect for further studies.

5.2.4. Applications for the recovered product as a fertilizer

The recovered phosphate can be reused as fertilizer directly or after processing by fertilizer industries. In the case of struvite recovery, for direct use, the product must meet the requirements of regulations, also in terms of method of preparation and the minimum nutrient content. Of the struvite recovery processes already implemented on real scale, only struvite resulting from the processes Pearl and NuReSys are certified as fertilizers in the USA, UK and Belgium. The Ash Dec process, for example, was licensed by the governments of Austria and Germany (Desmidt et al., 2015).

Biosolids can be defined as the sludge treated at a level that allows its application for different further uses or safe disposal (WEF, 2011; Tchobanoglous et al., 2015; World Bank Group and Development Bank of Latin America, 2018). Generally, the process for the production of biosolids consists of anaerobic digestion, alkaline treatment, composting and thermal drying (Mo and Zhang, 2013). Biosolids contain nutrients such as nitrogen, phosphorus, iron, calcium and magnesium (Tchobanoglous et al., 2015).

Sewage sludge can also be used as soil conditioner. Composting produces a biosolid with high concentration of organic matter accelerating the growth of plants and helping to control soil erosion and can be applied for landscaping and horticulture purposes. The main challenges in relation to the production of biosolids are public health and safety concerns regarding the quality of the product and acceptance of odour challenges (Mo and Zhang, 2013; Shi et al., 2018).

In Brazil, the application of treated sludge in soil is limited to few states. For example, in Paraná, located in the Southern region of Brazil, the treated sludge has been applied in agriculture for the cultivation of rice, coffee, sugarcane, soybeans and reforestation. Disinfection of the sludge is done through prolonged alkaline stabilization. The treated sludge is applied as a soil salinity corrector, providing savings to farmers who use it (Bittencourt et al., 2017).

In other developing countries, the application of sludge in agriculture is also performed in the conventional way of phosphorus recycling, as previously mentioned, through phosphorus recycling in organic form: direct application of sewage sludge in agriculture or for composting. Also, in some of these countries (China, Brazil, and some countries of the Middle East and North Africa region), there is the use of diluted wastewater for irrigation (indirect use), when the untreated wastewater is discharged into rivers, which are used for irrigation. However, this practice may cause water and soil pollution and represents health risks for crop consumers (Jiménez et al., 2009).

Depending on the technique used for nutrient recovery, whether from sewage (liquid phase), sludge or ash (solid phase), the recovered nutrients can produce several types of fertilizers (Tables 1–3): biomass (derived from techniques of biological accumulation of plants and algae) can be used as animal feed or as raw material for biofuel production; biosolids (solid product generated during anaerobic digestion for application as soil conditioner); biochar or ash (from thermal processes) for application as fertilizer in soil improving its properties; and chemical fertilizer (e.g., struvite) (Mehta et al., 2015; Puyol et al., 2017). Among these, the main product that has been commercially developed is struvite (Mehta et al., 2015).

Regarding the recovery of phosphorus, within the European Union, more than half of the phosphorus removed from wastewater in sewage treatment plants was reused or recycled in 2014 (EC, 2017). Lipińska (2018) reviewed the literature about EU regulations concerning water-sewage-sludge and the link with circular economy and concluded that the circular economy is a priority of the European Commission's economic policy for the coming years. Some of the challenges related to the concept of the circular economy in the European Commission are the need for further investments in the wastewater treatment sector, improvement of sewage sludge quality and its recovery, the reduction of the effects of stormwater overflows by promoting natural water retention systems or improvement of management in connection with sewage treatment plants, increase of wastewater reuse, optimization of energy consumption in wastewater systems and recovery of renewable energy from biogas at the plants (EC, 2017). Another issue that needs to be considered is the fertilizer application in organic farming, by adding recovered struvite to the list of approved fertilizers in EC 889/2008 (Blankesteijn, 2019).

According to Mehta et al. (2015), it is necessary to expand the development of nutrient recovery technologies, mainly phosphorus and potassium and to improve resource recovery efficiency. The presence of contaminants (soluble and insoluble) can affect the efficiency and economic viability of nutrient recovery processes, since in some cases the addition of pre-treatment or post-treatment may be necessary, increasing costs. Membrane filtration, which is one of the nutrient accumulation technologies, requires pre-treatment to prevent membrane fouling.

Many authors have recently discussed an integrated approach to resource recovery in wastewater treatment, considering processes that allow for the recovery of several resources: water, energy and nutrients (Cornejo et al., 2016; Khiewwijit et al., 2015; Leeuwen et al., 2018; Remy et al., 2016). Concerning phosphorus recovery, besides phosphorus itself, other materials associated with this mineral can be recovered in parallel (for example, nitrogen and potassium as struvite, and metals from sewage sludge), but the development of new cheap and efficient techniques to recover these other elements is needed (Mayer et al., 2016).

6. Benefits related to resource recovery

There are many environmental, economic and social benefits related to resource recovery from wastewater. Environmental benefits are protecting and improving the quality of surface water bodies, reducing water consumption and problems related to water availability, lowering greenhouse gas emissions, dropping the carbon footprint, reducing the use of landfills (for disposal of by-products generated by treatment units), reducing waste generation, lowering the use of fossil fuels, and recycling of nutrients (closing the cycle by returning nutrients to the soil) (Casiano Flores et al., 2018; Shore, 2017). The recovery of nutrients in wastewater units consequently reduces emissions associated with electricity generation in conventional fertilizer production processes (Tchobanoglous et al., 2015; Villarroel Walker et al., 2014).

Focusing on phosphorus recovery, the benefits are to provide an alternative and renewable source of fertilizer for food production, achieving significant savings due to the reduction of costs with sludge handling and disposal and reducing eutrophication in aquatic systems, since it generates very low effluent concentration of phosphate. Eutrophication is a problem often faced by developing countries, due to the discharge of effluents with high nutrient concentration (Sarvajayakesavalu et al., 2018).

The current increase in price of fertilizers due to scarcity of phosphorus negatively affects farmers and consumers in both developed and developing countries. Many developing countries cannot afford conventional chemical fertilizers (Sarvajayakesavalu et al., 2018). So, fertilizers based on phosphorus recovered from wastewater could be a promising alternative that also contributes to an increase in food security, especially in developing countries (Mayer et al., 2016). According to the International Fertilizer Industry Association (IFADATA, 2017), in developing countries, the imports of phosphate fertilizers were 12.17 Mt (mega-tonnes) of P_2O_5 while the exports were 10.48 Mt of P_2O_5, and the consumption (33.44 Mt) was higher than production (32.6 Mt P_2O_5) in 2016. In developed countries the consumption of phosphate fertilizer was 11.28 Mt and the production was 11.62 Mt of P_2O_5 during the same period. These data highlight the importance of phosphorus recovery initiatives especially in developing countries. The phosphate fertilizer imports and exports (both in Mt. unit) in the regions were 5.12 and 0.51 in Latin America, 0.99 and 3.51 in Africa, 3.25 and 0 in South Asia, 2.61 and 4.92 in East Asia, 0.54 and 1.95 in West Asia, respectively. East and South Asia are considered the largest market for phosphate fertilizer with higher consumption rates.

Phosphorus recovery can also have positive consequences from a plant operational point of view. For example, phosphorus recovery via struvite precipitation in anaerobic digestion liquors prevents scaling in pipes and pumps, which can improve sludge handling operations during wastewater treatment (Mayer et al., 2016).

In a broad context, the sustainable use of resources (through the implementation of resource recovery solutions) is a key element in achieving the sustainable development goals (SDG) as discussed elsewhere (Avellan et al., 2017; United Nations, 2015; United Nations, 2017). Therefore, in addition to mitigating environmental and health problems, implementing sewage treatment systems with resource recovery can generate social benefits (Trimmer et al., 2017).

Sanitation goals are expressed in SDG 6 (United Nations, 2015). Considering SDG 6.2, by 2030, access to adequate and equitable sanitation and hygiene for all should be achieved. Open defecation should be ended with special attention to the needs of women and girls and those in situations of vulnerability. According to SDG 6.3, the water quality should be improved by reducing pollution, eliminating dumping and minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater volume and substantially increasing recycling and safe reuse globally by 2030. The international understanding of 'sanitation' is related to the collection, treatment and disposal of wastewater. In an attempt to analyse the multidimensional effects of achieving sanitation goals while simultaneously integrating resource recovery, Trimmer et al. (2017) conducted a study in which they concluded that the replacement of existing sewage treatment systems with technologies of resource recovery could generate an increase in global nutrient and energy recovery potential of about 50–79%, suggesting that resource recovery should be the focus of actions in the creation of new sewage treatment systems and improvement (retrofitting) of existing installations.

Countries of Latin America and the Caribbean have the potential to double the use of both resources or completely eliminate unsustainable sources of nutrients and energy (Trimmer et al., 2017). These countries would benefit from installing wastewater treatment systems that combine nutrient and energy recovery. Some countries such as the ones located in West Asia would particularly benefit from investing in nutrient recovery from wastewater treatment (Trimmer et al., 2017). Thus, the use of bioenergy and nutrient recovery can contribute to improving people's quality of life and the environmental quality of developing countries (Avellan et al., 2017).

Each regional context has its own characteristics that must be considered in planning and choosing which resource to recover. In the case of nutrient recovery, rural areas show more promise in using recovered resources. For example, considering transport-related costs as a barrier, recovering nutrients in rural areas implies less logistical challenges than nutrient recovery in urban environments, which require further transport to rural areas if farming areas are distant of urban centres (Trimmer et al., 2017).

Resource recovery in addition to providing environmental benefits can provide economic benefits with monetary returns and broad social benefits with indirect economic value (Andersson et al., 2016). Villarroel Walker et al. (2014) estimated the monetary value of additional revenue generated by the implementation of different resource recovery technologies in the city of London. Among the recovery scenarios analysed were the pyrolysis of sewage sludge for energy recovery and the cultivation of algae to produce fuels and fertilizers. The results indicated that, comparing the different scenarios with each other, the income generated from the recovery of products (considering energy such as fuels and fertilizers) from the pyrolysis of sewage sludge was higher than the revenue resulting from the products recovered from algae cultivation. However, the outcome also depends on the current market value of the recovered product in each context.

Another economic benefit generated by resource recovery of treatment plants is the reduction of operational costs of the works, and generation of revenue since it will generate value-added products and may even commercialize carbon credits (Breach and Simonovic, 2018). In addition, by-products that previously required costly transport and disposal are now being valued, for example, sludge.

Although the benefits associated with the implementation of resource recovery strategies have been highlighted, it is important to consider that each alternative with its respective process and recovered resource may also have negative aspects as addressed in section 5.2.3. (e.g., energy, water and chemical consumption) and high initial costs, which should also be considered at the moment of decision-making. Therefore, the challenges linked to resource recovery have been outlined in the next section.

7. Identification of challenges

The wastewater treatment sector is facing a paradigm shift: wastewater treatment plants are not only planned as systems for pollution removal (end-of-pipe approach), but instead can be designed as factories where several products of value aggregate are subsequently recovered (resource-oriented approach) (Papa et al., 2017). However, currently this is not the case in most countries, especially in developing countries such as Brazil.

Renewable energy recovery has been considered easier to implement in practice when energy is used immediately on site to meet plant operational needs. The recovery of resources from sewage presents some barriers due to characteristics such as difficulties in handling and storage, possibility of contamination, difficulties in commercialization, and low public acceptance due to the perception that the recovered materials are still waste (Verstraete et al., 2016). The transition from pollutant removal by predominantly conventional wastewater treatment systems to resource recovery is not easy to be achieved, because wastewater treatment works were not designed for multiple purposes such as combined wastewater treatment, water reuse and nutrient recovery (Wang et al., 2018b).

Barriers and difficulties to implementation can vary depending on the resources available on site, scale of application and stakeholder perspectives (Trimmer et al., 2017). Table 4, based on a review of the literature, represents the current challenges to the recovery of resources in the treatment of sewage on the scale of wastewater treatment plants.

The factors highlighted in Table 4 are decisive to the implementation of resource recovery solutions for treatment plants. Some of these factors are interrelated; for example, the economic feasibility, market value of products and regulatory issues. Another aspect regarding the recovery of resources deals with the market for products recovered from wastewater. This should be part of the planning and decision-making process on which recovery options to choose, and their respective costs to produce, store and transport products and by-products.

About the lack of tools and methodologies to facilitate decision-making, some researchers have developed computational models that can help in cost-forecasting through the construction of scenarios taking into account operational and design characteristics, aiming at the integration of recovery technologies and optimization processes (Fernández-Arévalo et al., 2017; Puchongkawarin et al., 2015). However, the wide availability of technological options for treatment and recovery makes the process of choice and decision-making difficult (Puchongkawarin et al., 2015).

The necessary changes at treatment plant level to include resource recovery depend on the infrastructure and the processes already installed as well as the scale and type of products to be recovered.

Table 4
Summary of current challenges related to resource recovery from wastewater treatment works.

Aspect	Barrier	Reference
Technical	Lack of decision-making tools and methodologies to identify the best solution for each context; challenges in the measurement of environmental, social and economic benefits as well as impacts related to resource recovery	Morandi et al. (2018); Van Der Hoek et al. (2016)
	How to integrate and/or combine resource recovery solutions and maximizing plant productivity	Mo and Zhang (2013); Puchongkawarin et al. (2015)
	Wastewater treatment plant size	Bertanza et al. (2018); De Boer et al. (2018)
	Innovative technologies that require previous full-scale applications for testing	Puchongkawarin et al. (2015); Stamatelatou and Tsagarakis (2015)
	Risks related to contamination; quality of the final product	Verstraete et al. (2009); Verstraete et al. (2016)
Social	Social acceptance	Prouty et al. (2018); Verstraete et al. (2016)
	Stakeholders perception and perspective	Rao et al. (2017); Simha et al. (2017); Trimmer et al. (2017); Zijp et al. (2017)
	Public perception that wastewater and its byproducts are waste	De Boer et al. (2018); Sarvajayakesavalu et al. (2018); Verstraete et al. (2016)
Political or institutional	Regulatory policies; legislation; cooperation with stakeholders and institutions (e.g., network creation)	Casiano Flores et al. (2018); Harris-Lovett et al. (2018); Mayer et al. (2016); Papa et al. (2017); Sarvajayakesavalu et al. (2018); Verstraete et al. (2016)
	Lack of integrated approach (social, institutional and technical measures)	Sarvajayakesavalu et al. (2018)
	Changes to the existing infrastructure and its configuration	Bertanza et al. (2018); Puchongkawarin et al. (2015)
	Space availability; personnel skill limitations	Bertanza et al. (2018)
Economic	Market value of the recovered resources from wastewater; difficulties in the commercialization of the product	Ushijima et al. (2015); Verstraete et al. (2016); Blankesteijn (2019)
	Economic feasibility	Egle et al. (2016); Papa et al. (2017); Van der Hoek et al. (2016)

According to Bertanza et al. (2018), it is easier to plan a new treatment plant for the purpose of recovering resources than to adapt or upgrade the operations of an existing one.

Another key factor that interferes with a wastewater treatment plant's ability to incorporate resource recovery strategies is its size. According to Bertanza et al. (2018), for larger plants, the recovery of sludge, nitrogen and treated effluent as reclaimed water can be easier achieved compared to medium-sized and small plants.

The economic feasibility is also an important factor to be considered in choosing which resources to recover. In some cases, resource recovery can reduce maintenance costs for the wastewater treatment plant based on revenue generation. In this way, costs represent a very important criteria to be analysed for the implementation of a technology (Egle et al., 2016; Van Der Hoek et al., 2016).

In the case of developing countries, they cannot adopt high-cost recovery technologies (Sarvajayakesavalu et al., 2018). So, each context should be considered, prioritizing low-cost technologies. Other factors to be considered are the recovered amount of material and the generation of new waste and negative impacts of each technology (Egle et al., 2016; Van Der Hoek et al., 2016).

When considering the sanitation services chain, from the generation of wastewater at the source, through collection, transportation and treatment to reuse or final disposal, there are important relationships between several stakeholders and institutions that must be assessed. Some examples are the company responsible for sanitation services, the population, and the public organizations involved, who establish requirements and standards that must be met by the wastewater treatment facility operators (Rao et al., 2017). In the case of phosphorus recovery, there are several key stakeholders: the water boards that act as the suppliers of secondary phosphates, the fertilizer industry that functions as buyer of these phosphates, a certifying agency of fertilizers, and inter-organizational/semi-governmental agencies active in this field that act as brokers (De Boer et al., 2018).

When a resource recovery practice in wastewater treatment is proposed, the number of stakeholders involved increases. There will be participants who purchase the products (generated by works) such as farmers who purchase fertilizers, and industries that buy energy and reclaimed water. Environmental regulatory organizations will also get involved to uphold respective standards and legislation (Harris-Lovett et al., 2018; Rao et al., 2017). Therefore, the need for inter-sectoral policies is important so that the implementation of resource recovery strategies in treatment plants can be done in conjunction with other related sectors (World Bank Group and Development Bank of Latin America, 2018). A political support (including recommendations and targets) is a very important prerequisite for developing the phosphorus recycling sector (Nedelciu et al., 2018). Harris-Lovett et al. (2018) highlight the need for a nutrient management plan to support the transition from wastewater treatment plant to resource recovery facility.

Public policies, partnerships and the creation of networks between institutions from different sectors and financing mechanisms are factors that can encourage and accelerate the implementation of resource recovery strategies in wastewater treatment plants. The development of legislation concerning sewage sludge is important, since it influences quality standards, guidelines (e.g., for land application) and practices (Mayer et al., 2016; World Bank Group and Development Bank of Latin America, 2018). Usually, when new guidelines are published highlighting the need to reduce phosphorus release to receiving water bodies and the importance of nutrient recycling, as a result, new products and innovative technologies are likely to emerge on the market, which will encourage reuse of nutrients from sewage treatment (Andersson et al., 2016). Local governments and agricultural departments can play an important role in providing economic and other incentives including taxes, subsidies and recycling quotas to stimulate the adoption of phosphorus recovery strategies from wastewater treatment (Hukari et al., 2016; Sarvajayakesavalu et al., 2018). Consequently, these actions contribute to the creation of value from wastes and awareness between end-users such as farmers (Sarvajayakesavalu et al., 2018).

Phosphorus recovery processes have been shown to be technologically viable and have several real-scale applications. But there are technological, socio-economic and institutional constraints that limit the achievement of phosphorus recovery strategies on a regional and global scale (Sarvajayakesavalu et al., 2018). Table 5 presents barriers related to phosphorus recovery and specifically for struvite recovery.

Harris-Lovett et al. (2018) discuss the economic constraints related to phosphorus recovery. The cost of recovering phosphorus from wastewater is currently several times higher than the market price of rock phosphate. The value of struvite is rather low, and this sustainable product cannot compete against the relatively low cost of mined phosphorus at least for the time being. So, a struvite-based product has to be as efficient, affordable and predictable in releasing nutrients as existing materials to compete with conventional phosphate-based commercial fertilizers (Schipper, 2014). It is difficult to sell struvite to a

Table 5
Summary of current barriers related to phosphorus recovery implementation in wastewater treatment works.

Aspect	Phosphorus recovery	Struvite recovery[d]
Economic	Economic feasibility[a]; economic incentive[b]	Uncertainties in return on investment; conservative market; low price of phosphate rock and fertilizers
Political and institutional	National laws[a]; public policies[a]; efficient management in agriculture[c]; lack of integrated international governance[c]	No common interest; integrated approach is missing concerning recyclates per country; fertilizer regulations involving implementing P recovery technologies; regulations on the installation of P recovery technologies; recovered P product guidelines; transportation challenges; vested interests; complexity of stakeholders
Social		Negative public opinion due to the uncertainties of health issues; safety concerns; low awareness among farmers about struvite
Technical		Product safety is unclear; low solubility of struvite; struvite is not a stand-alone product; negative chemical characteristics of struvite; low maximum recovery yield

[a] Taken from Desmidt et al. (2015).
[b] Based on Harris-Lovett et al. (2018).
[c] Obtained from Sarvajayakesavalu et al. (2018).
[d] Based on De Boer et al. (2018).

bigger market such as the international scale (Blankesteijn, 2019). However, some waste streams that contain phosphorus can generate also other valuable products such as water, energy (via carbon) and metals. Consequently, these co-benefits are incentives to support phosphorus recovery and reuse (Harris-Lovett et al., 2018).

According to Sarvajayakesavalu et al. (2018), national support mechanisms are needed for cost-sharing, mainly for the developing countries; for example, a fair and equitable distribution of the costs of phosphorus recovery, financing of local specific innovations, and market adoption of existing technologies at scale.

There are challenges in terms of regulation, public acceptance, concerns about product quality and safety, economic feasibility, and lack of an integrated approach between stakeholders (Tables 4 and 5). When analysing struvite recovery, a low maximum recovery yield is notable, since higher proportions of phosphorus remain concentrated in sludge. A combination with other technologies for phosphorus recovery (from sludge or ashes) should be evaluated to stimulate and scale-up treatment plants.

Finally, the factors listed in Tables 4 and 5 should be considered for accelerating the implementation of treatment systems with resource recovery. There is an urgent need for innovation in sanitation approaches, including new business models, public policies, institutional partnerships, financial mechanisms, and educational measures to increase public acceptance to the product derived from wastewater. These factors can encourage and accelerate the planning and implementation of resource recovery strategies in treatment plants.

8. Conclusions and outlook

As outlined in this critical review, there are several available technologies for phosphorus recovery. Most of the technologies that are currently implemented at full-scale recover phosphorus from digester supernatant. Struvite is the most commonly recovered product. However, fertilizer based on struvite is still expensive, if compared with conventional fertilizer, so one possibility is combining phosphorus recovery with other valuable materials recovery to target more than one product, such as reclaimed water from treated effluent, metals and energy.

The main paths for phosphorus recovery are recycling from sewage sludge (for example, after anaerobic digestion and after dehydration of sludge), sludge water and sewage sludge ashes as well as conventional recycling through treated sludge application in agriculture.

The implementation of phosphorus recovery at full scale currently occurs in a few countries, which are mainly located in Europe, North America and Asia. Challenges to be addressed include the existing infrastructure, established treatment processes and the economic feasibility. Cities in developing countries are faced with high wastewater volumes and little space for treatment, and high amounts of sludge, which require proper disposal (usually in landfills) that is expensive due to reduced urban land availability. With the transition to phosphorus recovery, sludge should be a source for fertilizer production, reducing the need of space for disposal and the costs related to transport. Phosphorus recovery technologies can often be combined with existing configurations of treatment works.

It is important to assess how to maximize phosphorus recovery and minimize contamination risks associated with potential contaminants in the sewage sludge. Future research should focus not just on the development of new technologies or on how to improve the performance of existing ones, but also investigate how to integrate stakeholders' perspectives (e.g., those of end-users), and to identify the effects of regulations as drivers or barriers to facilitate the planning and implementation of phosphorus recovery in wastewater treatment plants with the insertion of the recovered product to the market.

Some challenges of future research are how to improve the phosphorus recovery efficiency and reduce its environmental impacts linked to energy consumption and reactant demands. Researchers should study how the phosphorus recovery technologies can be integrated with other resource recovery processes in parallel. There is also a need to improve sludge management policies and assess how they affect the resource recovery implementation in developing countries.

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Paper II

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A framework for resource recovery from wastewater treatment plants in megacities of developing countries

Mariana Cardoso Chrispim[a,b], Miklas Scholz[a,c,d,*], Marcelo Antunes Nolasco[b]

[a] Division of Water Resources Engineering, Faculty of Engineering, Lund University, John Ericssons Väg 1, P.O. Box 118, 22100, Lund, Sweden
[b] School of Arts, Sciences and Humanities, University of Sao Paulo, Arlindo Bettio Avenue 1000, Sao Paulo, Brazil
[c] Department of Civil Engineering Science, School of Civil Engineering and the Built Environment, University of Johannesburg, Kingsway Campus, PO Box 524, Aukland Park, 2006, Johannesburg, South Africa
[d] Civil Engineering Research Group, School of Science, Engineering and Environment, The University of Salford, Newton Building, Peel Park Campus, Salford, M5 4WT, UK

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ABSTRACT

In developing countries, there is often a lack of a comprehensive data set that supports the development of coherent policies on resource recovery from wastewater treatment. This paper aims to contribute to the elaboration of resource recovery projects by providing accurate and updated data from wastewater treatment plants such as those located in the region of the Macrometropolis of Sao Paulo. The authors discuss possibilities of improvement of resource recovery for this illustrative example. Comprehensive analyses were performed based on data from 143 municipal wastewater treatment plants to understand the situation regarding resource recovery implementation in this region. The results show that just 26% of the plants perform at least one resource recovery practice. The predominant resource recovery practice is internal water reuse, and recovery is concentrated more in large plants than in medium and small ones. The sludge is disposed in landfills except for three plants, which perform sludge recycling for compost. Some plant managers reported interest in recovering energy from biogas, in expanding water reuse and in recovering sludge for fertilizer production or for building materials. Several aspects that have been regarded as relevant to the implementation of resource recovery processes in previous literature are discussed, such as the size of the plant, related legislation as well as treatment technologies and configurations. Finally, the authors propose a generic framework with several steps that can help to achieve resource recovery implementation. Therefore, the results can provide support for planning of resource recovery projects for large cities in developing countries.

1. Introduction

Wastewater contains important resources that should be recovered in wastewater treatment plants to generate value-added products such as renewable energy, biofertilizers and water for different purposes. The recycling of resources through innovative recovery processes is only a recent objective in wastewater treatment systems (Mehta et al., 2015; Rao et al., 2017) and makes the processes of the plants more efficient; it reduces the amount of waste and it provides environmental and economic benefits. Some of the key resources that can be recovered are nutrients and energy.

Regarding nutrient recovery, it provides sustainable use of phosphorus (Sarvajayakesavalu et al., 2018), produces a high-quality effluent with low phosphorus concentration, which mitigates eutrophication risks in water bodies as well as produces an alternative source of fertilizer, alleviating phosphate rock reserves (Chrispim et al., 2019). Regarding eutrophication, Lwin et al. (2017) estimated the amount of phosphorus flowing from agriculture and domestic wastewater and concluded that India, China, Brazil and USA will be the countries with the largest flows of phosphorus by 2100.

A promising solution for wastewater treatment systems is energy recovery, since wastewater contains chemical, thermal and hydraulic energies. In a conventional wastewater treatment plant, it is possible to recover energy in the effluent treatment or in the sludge line to supply at least a substantial part of the wastewater plant's energy demand (Đurđević et al., 2019). The ultimate aim would be for the plant to become energy self-sufficient with zero external energy supply (Svardal and Kroiss, 2011). As there is substantial energy consumption during several stages of the treatment (sewage collection, transportation, effluent treatment, sludge treatment and disposal), energy recovery in a

* Corresponding author. Division of Water Resources Engineering, Faculty of Engineering, Lund University, John Ericssons väg 1, P.O. Box 118, 22100, Lund, Sweden.
E-mail addresses: mariana.chrispim@usp.br (M.C. Chrispim), miklas.scholz@tvrl.lth.se (M. Scholz), mnolasco@usp.br (M.A. Nolasco).

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wastewater treatment plant can reduce electricity costs.

In the context of the perspectives described above, there is a need for energy, water and waste systems to be analysed by a nexus approach to move towards more sustainable cities (Wang et al., 2018a) characterised by water conservation and the efficient use of natural resources. According to Mo and Zhang (2013), sustainability in wastewater management needs to consider not only treatment of sewage, but also the potential for resource recovery from the treatment.

However, most of the wastewater treatment installations currently only aim for sewage treatment and final disposal into the environment. Papa et al. (2017) analysed 600 plants in Italy to understand the situation of resource recovery, and concluded that 60% of the works did not perform any kind of recovery. The most common recovery options in the plants with resource recovery were internal water reuse from treated effluent and sludge reuse for agricultural application. So, these systems did not reach their maximum potential of resource recovery.

Especially in developing countries, there is a lack of reliable, recent and detailed data regarding wastewater flow rates, treatment performance as well as recovery actions from wastewater works (Sato et al., 2013; Malik et al., 2015; Mateo-Sagasta et al., 2015) and solid waste recycling (Harris-Lovett et al., 2018). Consequently, quantifying the current situation of resource recovery in developing countries is a challenge. According to Guven and Tanik (2018), assessments of applications of water use and energy recovery from wastewater treatment plants in developing countries are generally lacking. The available information does not use uniform terminologies and units to describe current practices, making it difficult to compare data or establish global inventories (Jiménez et al., 2010).

Most of the publications on this topic (Van Der Hoek et al., 2016; Kretschmer et al., 2016; Leeuwen et al., 2018) do not cover developing countries. Coats and Wilson (2017) state that real implementation examples of resource recovery remain relatively scarce in the literature. For instance, there is a shortage of research that addresses the implementation of resource recovery actions for different locations in Brazil, where little progress has been made in collecting data to support the development of coherent policies in resource recovery. Few studies have addressed how to integrate resource recovery technologies in municipal wastewater treatment processes. Borges et al. (2015), Santos et al. (2016), Bressani-Ribeiro et al. (2017) and Rosa et al. (2018) analysed energy recovery in some plants in Brazil. Moreover, only some studies (Chrispim et al., 2017; Paulo et al., 2019) were based on decentralized and source-separation sanitation systems.

Besides analyzing measures and technologies from technical, economic and environmental aspects, it is necessary to implement inventories of the quality and the quantity of the resources in municipal wastewater, the current application status as well as opportunities and challenges for future implementation. Sato et al. (2013) state that this type of information on wastewater generation, treatment and use are crucial for decision-makers, researchers and practitioners for the development of national and local plans aiming at safe wastewater reuse and for assessment of the potential of resource recovery at different scales.

The introduction of resource recovery strategies into existing wastewater treatment systems or into new facilities is particularly interesting for megacities and urban agglomerations. In these areas, there is significant scarcity of natural resources to meet the population demand and a need to improve wastewater treatment services (Wang et al., 2018b). These cities have larger impacts on water resources than smaller urban or rural settlements for several reasons. Because of the large quantities of surface water that may be diverted, the water supplies to downstream users are affected. In addition, as a result of inadequate wastewater management, surface waters can become severely polluted, compromising the quality and availability of future supplies and creating health risks (National Research Council, 1996). Therefore, the main challenges include improvement and expansion of the population's access to water and wastewater services (National Research Council, 1996; WHO, 2018).

Because of their high population, large cities require massive quantities of energy, water and food provision (Khan et al., 2006). So, resource recovery strategies for wastewater treatment plants in megacities could mitigate some of these problems by supplying water, energy or raw materials for products to meet the demand, and simultaneously provide economic benefits from the recovered products. The reduction of operational costs (Catarino et al., 2007) relates to the disposal and treatment of byproducts such as sludge. Environmental benefits include improvement of the effluent quality and reduction of emissions.

In the case study country Brazil, the most populous region is located in the State of Sao Paulo. The term Sao Paulo might refer to four different levels. The State of Sao Paulo (level 1) comprises several regions including the region of the Macrometropolis of Sao Paulo (level 2), which is one of the largest urban settlements in the world, concentrating more than 33 million inhabitants and accounting for 50% of the urbanized area of the State of Sao Paulo and for 75% of its population (São Paulo Metropolitan Planning Company S/A (EMPLASA), 2019). The region of the Macrometropolis of Sao Paulo comprises eight urban agglomerations. One of these agglomerations is the Metropolitan Region of Sao Paulo, also known as Megacity of Sao Paulo (level 3) (The United Nations, 2018). This megacity includes the City of Sao Paulo (level 4). For reasons of simplicity, in this paper, the authors will refer to the above four levels as state, region, megacity and city, respectively, if and when the official meaning is clear from the context. However, this study is mainly concerned with the region (level 2).

The region of Sao Paulo faces several challenges regarding water and sanitation infrastructure. Considering that it is a very populous area, water management is a complex issue. According to projections for the coming years, there is a trend to increase both the water demand and the population in this region (The Department of Water and Electric Power (DAEE), 2013). The qualitative commitment of the water sources used for human supply and the low water availability characterizes a critical scenario in this area. Considering its size, rapid population growth, high population density and economic situation, the region has been chosen as a representative case study for other megacities in developing countries, which face similar conditions such as water scarcity and inadequate wastewater treatment and collection.

In this context, tools that facilitate the process of planning and decision-making are necessary and allow for more cost-effective and sustainable means to recover resources from wastewater. This paper aims to produce organized and reliable data related to resource recovery application in megacities in developing countries to support and facilitate the transition to sustainable wastewater treatment plants through the assessment of the potential of resource recovery implementation at different scales in an effective way. The corresponding objectives are (a) to analyse the current situation of existing plants in the region of Sao Paulo used as a representative case study regarding the implementation of resource recovery solutions; (b) to identify relevant factors that can stimulate and support the implementation of resource recovery from wastewater treatment; (c) to suggest potential areas for improvement in the respective case study such as interventions of resource recovery technologies; (d) to propose a generic framework to facilitate the planning and implementation of resource recovery in plants; and (e) to discuss briefly the results of the case study region and other megacities in developing economies.

2. Methodology

2.1. Region of Sao Paulo (study area)

The region of Sao Paulo is located in the State of Sao Paulo and includes 174 municipalities. The demographic density is 630.5 inhabitants/km^2. This region has significant socio-economic importance and is well-industrialized, including diversified commerce, complex services and a productive agroindustry (EMPLASA, 2019). It represents

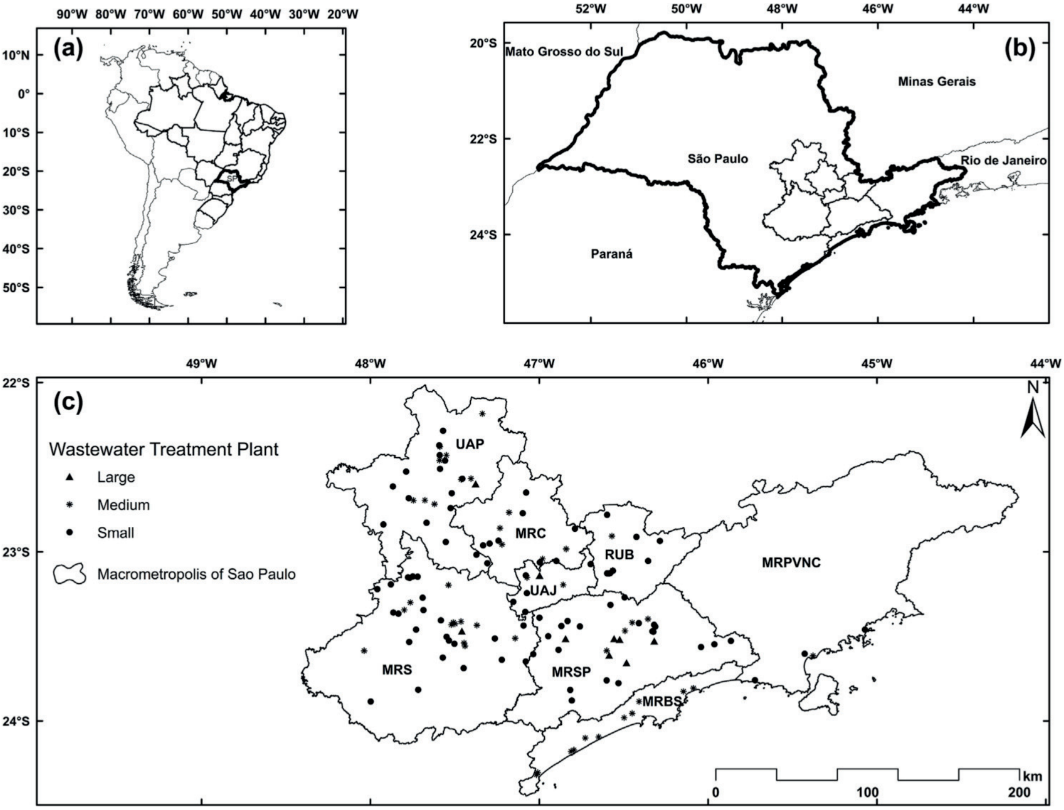

Fig. 1. (a) Map of geographical location of Brazil, highlighting the State of Sao Paulo in bold; (b) Macrometropolis of Sao Paulo location in the State of Sao Paulo; and (c) locations of the 143 wastewater treatment plants in the metropolitan regions and urban agglomerations. RUB, Regional Unit Bragantina; UAJ, Urban Agglomeration of Jundiaí; UAP, Urban Agglomeration of Piracicaba; MRBS, Metropolitan Region of Baixada Santista; MRC, Metropolitan Region of Campinas; MRS, Metropolitan Region of Sorocaba; MRSP, Metropolitan Region of Sao Paulo; MRPVNC, Metropolitan Region of the Paraíba Valley and the North Coast.

83% of the state gross domestic product (GDP; 1.61 trillion reais, equivalent to 0.4 trillion US dollars) and represents about 27% of the national GDP (referring to the GDP of 2015) (Senese Neto, 2018). The region of Sao Paulo comprises five metropolitan regions and three urban agglomerations (EMPLASA, 2019) (Fig. 1).

In the state of São Paulo, tropical climate dominates the central region of São Paulo. This climate is characterised by a rainy season in summer, a dry winter and an average temperature of over 22 °C in the warmest month. In some mountainous areas, the average upper temperature is below 22 °C in the warmest month. In the higher areas (Serra do Mar and Serra da Mantiqueira), summer is milder and rainier. The coast has a tropical rainy climate without a dry season and average rainfall of the driest month exceeding 60 mm (Sao Paulo State Government, 2018). The Köppen Climate Classification subtype predominant in the study area is “Cfa” (Humid Subtropical Climate) (Weatherbase, 2020).

The region of Sao Paulo presents several challenges related to water management. The megacity of Sao Paulo is an example of this problem, since it concentrates more than 10% of the inhabitants of Brazil in less than 0.1% of its corresponding territory. Moreover, the megacity has low water supply provision. Several municipalities within the region have high industry activity and agricultural production. The coastal area is also subjected to water scarcity, especially because of the intensive water consumption by complex industries, and an increase in water demand during the holiday season (Ribeiro, 2011).

Most surface water bodies within the region are polluted due to urban sprawl (Tagnin et al., 2016). In 2010, there were 3.8 million people living in favelas (Sayuri, 2014), with lack of access to proper wastewater collection and treatment as well as absence of safe water supply. Favelas are known as low and middle-income unregulated neighbourhoods experiencing governmental neglect.

Due to the mentioned characteristics, highlighting the problematic of water vulnerability (National Water Agency (ANA), 2014), the high population concentration, socio-economic urbanization characteristics, the great consumption rate of natural resources and climate zone, the region of Sao Paulo was chosen as a representative case study for other megacities in developing countries.

2.2. Resource recovery implementation survey

The procedure for the survey of wastewater treatment plants in the study region to assess the corresponding resource recovery implementation is outlined in this section. This process was divided into three phases: 1) Definition of the sample in the study area and contact with the organizations responsible for the works; 2) questionnaire for data collection; and 3) data analysis.

2.2.1. Phase 1

This phase comprised the following steps: survey of contacts, communication with the managers and sending of questionnaire. First, the organizations responsible for the plants in each of the 174 municipalities belonging to the region were identified. Regarding the municipalities where the Sao Paulo State Water and Sewage Services Company is the authority responsible for wastewater treatment, the managers of each sub-region were contacted. For the other cities, where other organizations are responsible for wastewater treatment, data were obtained from other sources such as the Water and Sewage Services Diagnostics of the National Sanitation Information System (SNIS, 2018), the websites of the Regulatory Agency of Sanitation and Energy of the State of Sao Paulo (ARSESP, 2019) and websites of the city councils (specifically those linked to the department/secretary managing wastewater treatment; e.g., the municipal secretary of sanitation). For private companies, their respective websites were searched. After this step, the department and the manager responsible for the wastewater treatment services of each municipality received the questionnaire.

2.2.2. Phase 2

In order to collect the data in relation to the resource recovery actions implemented in the wastewater treatment plant, an easy-to-fill-in questionnaire was prepared based on Papa et al. (2017). The questionnaire consisted of two sections: preliminary questions and specific questions about the existence of resource recovery options (Fig. 2). Supplementary Material 1 contains the questionnaire.

The questionnaires were sent by e-mail with an informed consent form to educate the participants about the purpose of the research, following ethical standards. All data collected with the questionnaires are relevant for the period between July 2017 and April 2019. In some cases, managers were contacted with additional questions via e-mail or telephone to clarify the collected information.

2.2.3. Phase 3

After data collection, both qualitative and quantitative data from questionnaires were organized into data spreadsheets for comparison purposes. The results were parameterized according to the size of the plant with three classes being established according to the Brazilian Resolution 377 of the National Environment Council (CONAMA): small WWTP with a wastewater inflow rate ≤50 L/s or a population equivalent of up to 30,000 people; medium-sized plants: the plant with a nominal wastewater inflow rate > 50 L/s but ≤400 L/s, or with a capacity to serve 30,000 to 250,000 inhabitants; large plants: the plant with an inflow > 400 L/s and with a capacity of supporting more than 250,000 inhabitants (National Environmental Council, 2006a).

Within the region of Sao Paulo, there are cities without any wastewater treatment. Also, some cities sent their sewage to plants belonging to other municipalities nearby. In order to estimate the number of wastewater treatment plants within the case study region, the authors referred to the questionnaire answers. Concerning non-responsive municipalities, the authors consulted two national databases: Atlas Sewers: Depollution of Water Basins from the National Water Resources Information System (SNIRH), which contains information about the number of plants for each Brazilian city (SNIRH, 2013); and the Information System on Sanitation for Sao Paulo State (SISAN, 2016) that contains the municipal plan of sanitation for each municipality. Based on this, it was possible to estimate the total amount of plants and to calculate the percentage of the responsive plant managers.

Based on questionnaire findings, existing resource recovery initiatives were mapped and described. Then, the key factors that can affect the implementation of resource recovery were identified and potential areas for improvement were discussed. The authors identified what can be done in the future to develop sustainable works based on successful examples that are already underway in the region. The

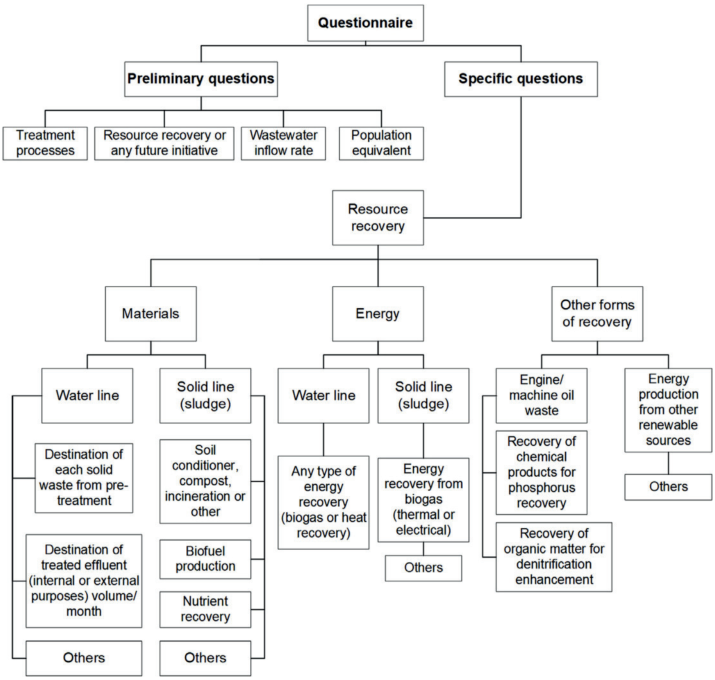

Fig. 2. Summary of the content of the questionnaire provided to the managers of wastewater treatment plants located in the Macrometropolis of Sao Paulo.

results were discussed, and key measures of resource recovery were recommended.

2.3. Framework creation

The authors propose a new generic framework for planning and implementation of resource recovery. This framework was initially derived based on the results from the conducted survey. For step 9 of the framework, indicators were selected based on various references. Technical indicators were after Sikosana et al. (2017), Van Der Hoek et al. (2016) and Harris-Lovett et al. (2018). Economic indicators were influenced by Sikosana et al. (2017). Environmental indicators were inspired by Hu et al. (2016). Finally, societal indicators as well as institutional and political ones were based on Woltersdorf et al. (2018).

3. Results and discussion

3.1. Overview

The findings are organized in six sections: (1) Findings obtained from the questionnaires and a discussion on how practices vary in the different metropolitan regions; (2) the key factors that affect the implementation of resource recovery; (3) possibilities for resource recovery strategies that could be implemented in the study area, considering the local context; (4) a proposed framework as a tool to stimulate/support planning and decision-making; (5) a comparison between the region of Sao Paulo and other megacities concerning resource recovery from wastewater treatment; and (6) limitations of this study.

3.2. Implementation of resource recovery measures

About 53% of the total number of plants in the region of Sao Paulo were analysed. This equates to 143 facilities located in 75 municipalities across the region. The proportion of plants with responses for each metropolitan region was 100% for MRBS, RUB and UAJ, 85.7% for MRSP, 77.1% for MRS, 67.5% for UAP, 20.3% for MRC and 7.9% for MRPVNC (see Fig. 1 for meanings of abbreviations). From the total (143) analysed, just 37 plants performed at least one resource recovery strategy (not considering the recycling of oil waste). The only other form of recovery mentioned was the separation of equipment-related oil waste, which is collected and conveyed to appropriate facilities for recycling.

Regarding the surveyed plants with some resource recovery action, the situation varies among different metropolitan regions. Considering the plants with surveyed data, the metropolitan area with the highest predominance of resource recovery plants is Baixada Santista (76.9% of the total of plants). Fig. 1 displays the distribution of the plants in the study area.

Fig. 3 shows the general results for the situation of the implementation of resource recovery strategies from wastewater treatment in the region of Sao Paulo. As can be seen, few plants currently include resource recovery practices. Only 26% of the surveyed plants performed at least one resource recovery action. Among the plants with resource recovery, it can be noted that water reuse for internal purposes was the most common resource recovery action implemented in this region. This finding agrees with the results reported by Papa et al. (2017), where water reuse was the most common resource recovery practice. The prevalence of internal reuse over external reuse was expected since reclaiming water externally involves several other variables such as specific effluent quality requirement compliance, market demand in the surrounding area, higher investments and infrastructure of distribution of the reclaimed water (e.g., pipes or trucks) to the destination. Supplementary Material 2 shows the distribution of all resource recovery practices in the region of Sao Paulo.

Considering the group of plants with internal reuse, the predominant uses for reclaimed water were washing and cleaning of courtyards as well as landscape irrigation (57.1% of the plants), sludge dewatering processes with polymers, cleaning of centrifuges and screens (45.7%), washing of sewage treatment equipment and reactors (40%), cleaning and unblocking of sewage collection networks (20%) and others (sewage lift station, preparation of chemicals and toilet flushing) (20%). The total volume of water reused (considering the plants that perform internal reuse and with response for this question) was about 405,094 m^3/month.

In relation to the plants that practice external water reuse, the applications are mostly (present in 44% of the plants with external reuse) for industrial purposes such as cooling towers, (textile) industry, civil (and ground) construction companies, laundries and urban use. The latter includes irrigation of parks, firefighting, washing streets after fairs, washing of trucks for transportation of recycled waste, transportation (airplanes and trains), urban cleaning, clearing of rain gutters and sewage pipes, washing of courtyards and cleaning of public streets and squares. Considering the responses from the plants, which perform external reuse ($n = 9$), the total was 1,176,516 m^3/month. In 2018, the plants located in the megacity of Sao Paulo marketed a volume of 1,461,470 m^3 of reclaimed water. This figure does not include the volume provided by the Aquapolo Project (see below). In spite of this, the reclaimed water supplied at nominal plant capacity was 38.3%. In comparison, the reclaimed water sold as treated effluent was only 0.43% (SABESP, 2018a), which indicates that the production and commercialization of reclaimed water is relatively low.

Some treatment plants implemented more robust technologies such as the combination of physicochemical processes. This is the case for two plants with a high volume of reclaimed water for external reuse. They comprise tertiary treatment. One of these plants is located in Sao Paulo city and has tertiary treatment by granular filters, cartridge filters and chlorine for disinfection. The other plant is part of the Aquapolo Project and comprises disc filters (400 μm), anoxic reactors, aerobic reactors, membrane bioreactors (0.05 μm pores) and reverse osmosis units, producing an effluent of high quality reclaimed water. The Aquapolo Project is an advanced water reuse plant for industrial purposes. In this works, the ABC plant effluent is the supply source to the Aquapolo Project's treatment system, which serves a Petrochemical Complex (SABESP, 2018a). The volume of treated effluent from the ABC WWTP to the Aquapolo project was 1,044,576 m^3/month for the period from January to June 2017.

Regarding sewage sludge, Fig. 3 shows that just three plants recycle nutrients from sludge through composting and subsequent fertilizer production. In all the other plants, the sewage sludge is disposed via landfills. The results of Ribarova et al. (2017) showed that disposal via landfills and temporary storage at wastewater treatment sites were the most common destinations for sewage sludge. Their study indicated that about 26% of the total generated sludge was used in agriculture. In other developing countries such as China, landfilling is also the most common option (about 50%) of treated sludge disposal (Zhang et al., 2016).

In this study, one similarity was observed between the three plants with sludge recycling: the existence of partnerships with private companies and/or with universities. In one of these plants, there was an experimental study collaboration with the Faculty of Agronomical Sciences. At the Jundiai plant, the composting facility was built inside the wastewater treatment area to minimize costs of transport. The operators use dried sludge combined with other organic solid waste (e.g., wood chips, chopped urban pruning, sugarcane bagasse and eucalyptus husk) for composting, resulting in commercial organic fertilizer production for agriculture supported by a spin-off company.

Concerning the surveyed plants, the fertilizer has been accredited by the Brazilian Ministry of Agriculture, Livestock and Food Supply as a safe product, and it is therefore used for cultivation of corn, sugarcane, coffee, apple, orange, soy, citrus, eucalyptus and flowers. However, there is a restriction for crops where the eatable parts have been in

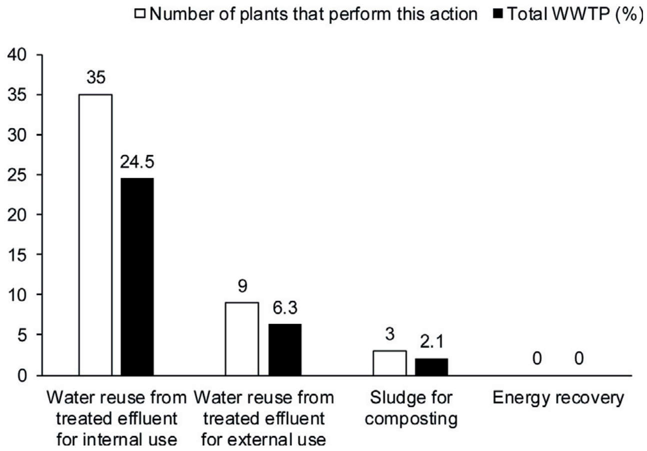

Fig. 3. Implementation of resource recovery options in the surveyed wastewater treatment plants in the Macrometropolis of Sao Paulo. Data from 143 wastewater treatment plants collected between 2017 and 2019. Note that there were plants that performed more than one action.

contact with soil such as roots, tubers and vegetables. About 28,000 tonnes per annum of fertilizer are being produced from thermophilic composting at the Jundiai plant.

Another important finding of this study is that there is no energy recovery in the surveyed plants. Although several of them produce biogas through anaerobic processes (Table 1), it is not used sustainably but flared. According to the response of some managers, the main reason for not recovering the biogas was that the generated volume is too low and that recycling is therefore not economically feasible. They also mentioned that some previous studies were undertaken to estimate the potential of biogas recovery. However, follow-up statements indicated that some managers do lack knowledge about energy recovery solutions.

According to the Brazilian Association of Biogas (ABIOGAS, 2019), in 2018, there was a potential of 5.8 billion Nm^3 biogas production linked to the sanitation sector in Brazil. Forbes et al. (2018) evaluated the feasibility for biogas recovery for power generation and/or thermal heat production for three plants with anaerobic digestion in Brazil. The results were promising for two of the analysed utilities (wastewater inflow rates of 1500 L/s and 2290 L/s). The benefits of installing biogas utilization facilities include the production of electrical and thermal power as well as the reduction of biosolid volume, energy bills, expenses related to sludge transport and disposal, and revenue from sale. For a plant with low capacity (350 L/s), the financial analysis was not favourable, mainly due to the estimated costs of producing electricity, which was higher than the corresponding purchase price. So, as anaerobic digestion and biogas utilization facilities have strong economies of scale, their unit costs tend to decrease and become more attractive as processing capacities increase. Some difficulties related to biogas utilization in Brazil are the high cost of equipment, too few cogeneration (combined heat and power) projects, absence of good data, lack of operator's knowledge of cogeneration systems; potential need for additional staff, lack of area available for new equipment and limited governmental incentives (Forbes et al., 2018). Santos et al. (2016) evaluated the economic viability and the potential of energy generation by biogas in anaerobic plants in Brazil. Their results indicated economic viability only for cities with populations greater than 300,000.

In the study region, some measures that could be applied to stimulate energy recovery are (a) the creation of partnerships with private companies and/or with universities to share knowledge and support on energy recovery technologies and operation; (b) partnership with other wastewater treatment facilities in Brazil, which already have practical experience and perform biogas recovery (e.g. in Paraná State); (c) economic incentives from government, for example, to buying equipment; and (d) co-digestion with organic food waste or combined with biogas from sanitary landfill could be done to increase biogas production. Felca et al. (2018) highlighted the need of public policies to support the generation of energy from renewable sources, lack of research and lack of investment in biogas in Brazil.

Regarding the existence of on-going project and future initiatives of resource recovery, managers of 25 plants answered positively (17.5% of the total of plants). The recovery practices reported were sludge recycling for fertilizer or soil conditioner (16 plants), biogas for energy recovery (6), external water reuse (5) and sludge reuse for civil construction materials (3).

Some plant managers replied that studies were already performed to evaluate the potential of biogas and sludge recovery. One mentioned a study for assessing the potential for biogas recovery. Two other plants already performed studies for evaluating the use of sludge in bricks, tiles or as fuel for ovens. Their results indicated that these solutions could be applied under favourable economic and technical boundary conditions. Three other plant managers expressed an interest in transforming sludge into fertilizer, depending on favourable legislation. One example is Campinas municipality, where there is an intention to compost sludge to produce biofertilizer. There is a current agreement with the city council and a company to recycle urban organic waste (tree pruning waste, fruits and vegetables together combined with sewage sludge) to be treated in a composting process. Also, in the same city, there is a project to expand the reuse of water (from treated effluent) through pipes connecting the reclaimed water to the Airport and Industrial Park of Campinas. In addition, some new plants are being built with the goal of water reuse and another one is being retrofitted for tertiary treatment as well as nitrogen and phosphorus removal for production of water for reuse from the treated effluent.

Some plant managers reported interest in initiatives for recovery of biogas. This is the case for the five largest plants in the megacity of Sao Paulo. It includes the project entitled Waste to Energy Barueri. Barueri is the largest wastewater treatment plant in South America with a wastewater inflow rate of 10.84 m^3/s. This plant receives more than half of the treated wastewater of the megacity. In this plant, the implementation of a pilot plant for sludge thermal treatment using plasma technology is being considered. It aims to reuse sludge either for energy

Table 1
Different municipal wastewater treatment plant (143 plants) processes in the region of the Macrometropolis of Sao Paulo, and corresponding possibilities of resource recovery.

Type of data	Treatment process configuration						
	Secondary treatment line				Sludge line[d]		
	Activated sludge[a]	Pond systems[b]	Anaerobic reactors[c]	Others	Thickening	Anaerobic digestion	Dewatering
Proportion of plants (%)	38.5	30.8	21.7	9.0	21.7	2.8	46.9
Potential of resource recovery	Water reuse[e] and phosphorus recovery	Water reuse[e] and energy recovery	Water reuse[e] and energy recovery	Not applicable	Phosphorus recovery from supernatant and sludge for reuse	Phosphorus from digester supernatant and biogas for energy recovery	Phosphorus from dewatering effluent, biosolids for fertilizer, sludge for composting (or to manufacture building materials) and biosolids as source for valuable metals
Usage possibilities	Internal purposes or external reuse	Power supply (on-site and external)	Power supply (on-site and external)	Not applicable	Application in agriculture	Application in agriculture and power supply (on-site and externally)	Application in agriculture and insertion of the recovered products into the market

[a] Includes batch, continuous and extended aeration as well as the activated sludge process followed by a moving bed biofilm reactor.

[b] Includes the following: aerated pond and settling pond (with or without disinfection); aerated pond, settling pond and maturation pond; anaerobic pond and facultative pond maturation; anaerobic pond, aerated biological filter and settling tank; anaerobic pond, aerobic pond and maturation pond; anaerobic pond and facultative pond; facultative and settling pond; facultative pond (with or without disinfection); facultative pond and maturation pond; aerated pond, anaerobic filter, secondary clarifier and disinfection; and stabilization pond with aeration and mixing as well as settling pond; anaerobic pond, facultative pond, flotation with diffuse air and disinfection.

[c] Includes anaerobic reactor followed by aerobic reactor; upflow anaerobic sludge blanket (UASB); UASB and submerged aerated filter; combined systems of UASB and aeration tanks; UASB and ponds.

[d] The data do not include the following cases: plants without sludge line, where the sludge is stored and subsequently transferred to other large plants; mainly pond treatment where the removal of sludge does not occur at a fixed frequency or the sludge is removed after 10 or 20 years; and replies with no specifications for the sludge line.

[e] Depending on water quality and regulatory requirements.

recovery or for civil construction material. In this process, the sludge is subjected to high temperatures of around 1500 °C. An inert vitreous residue with a drastic reduction of the initial volume is being created. There is a possibility of application of the material in the construction sector (SABESP, 2017; SABESP, 2018b).

Harris-Lovett et al. (2019) undertook a survey with stakeholders (diverse groups of regulators, wastewater managers, coastal stewards, researchers as well as advocates for environmental or industrial causes) to analyse their preferences concerning nutrient management options and corresponding objectives. Most stakeholders mentioned the option of recycling treated effluent to irrigation to increase resource recovery. In comparison, concerning the region of Sao Paulo, the option of reuse of treated effluent for irrigation in agriculture was not mentioned by the managers, probably because there is not yet local regulation for water reuse in agricultural irrigation, except for the irrigation of landscapes and green areas.

3.3. Factors that affect resource recovery implementation

Some managers reported the following barriers to resource recovery implementation: low amount and quality of biogas; no possibility of energy recovery due to the type of biological treatment through ponds (not true according to the authors' understanding), impracticability of the current legislation for sludge reuse and the low demand for reclaimed water in areas close to the plant. These factors and others reported in the previous literature are discussed below.

According to Bertanza et al. (2018), a key factor that interferes with the ability of plants to incorporate resource recovery strategies is the corresponding scale of operation. For larger wastewater treatment works, the recovery of the corresponding effluent as reclaimed water and the retrieval of major nutrients from sludge can be easier achieved, while potential restrictions are linked to small- and medium-sized works. In relation to this aspect, most of the plants, which perform at least one type of resource recovery, are large- and medium-sized (Table 2). The classification of size is based on Resolution CONAMA 377 (National Environmental Council, 2006a). Supplementary Material 3 shows the distribution of wastewater treatment plant size and inflow rates in the region of Sao Paulo, and Supplementary Material 4 contains the raw data for the surveyed plants. Results indicate that the size of the plant affects its ability to implement resource recovery. Most of the large plants performed resource recovery, while few of the small ones recovered resources. This is likely due to the constraints in investment (economies of scale) for small plants (Papa et al., 2017). Hanna et al. (2018) compared the energy consumption in wastewater treatment facilities and also noticed that larger facilities are usually more energy-efficient in terms of volume of water to be treated. In addition, larger facilities are able to invest more money in their installations and can therefore afford newer and more efficient equipment such as process control systems.

Although in this study we considered a Brazilian regulation to classify the size of plants, the distribution of them in relation to size was similar to another study in the USA (Diaz-Elsayed et al., 2019). Overall, the results in this study showed a higher number of small plants compared to large ones, considering the region of Sao Paulo. Diaz-Elsayed

Table 2
Size distribution of the wastewater treatment plants (see also Supplementary Material 3) and corresponding indication of resource recovery implementation.

Size of plant	Number of plants	Number of plants with resource recovery	Proportion (%)
Small	86	4	4.7
Medium	47	25	53.2
Large	10	8	80.0

Note: The classification of size was based on Resolution CONAMA 377 (National Environmental Council, 2006a).

et al. (2019) found that almost 80% of the wastewater treatment plants are of small or medium size (below 10,000 population equivalent), and about 20% plants are classified as large. According to their findings, the strategies of energy recovery from wastewater are more prevalent in large-scale plants in the form of biogas and/or electricity generated from sludge.

Besides the plant size, another important aspect is location. Concerning rural and semi-urban areas, it may not be economically feasible to implement resource recovery technology such as phosphorus recovery, because of the low recovery rate and the elevated cost of innovative technology. Therefore, Sarvajayakesavalu et al. (2018) propose farmland application of sludge as a viable alternative for recovery of phosphorus.

Legislation is an important aspect to consider when planning resource recovery implementation. For example, water reuse regulations are important to incentivise the wastewater treatment plants to produce water for reuse from their treated effluent. In the State of Sao Paulo, the Joint Regulation SES/SMA/SSRH n.1 (Sao Paulo State Government, 2017) governs the non-potable direct reuse of treated wastewater for urban purposes. This was an important milestone in establishing guidelines and criteria for non-potable direct water reuse. The categories covered by this resolution are landscape irrigation, washing of streets and other public and private spaces, civil construction, clearing of rainwater galleries and sewage networks, car washing, and firefighting. The use of treated effluent for irrigation, agriculture, grazing and forestry are not included. In this regulation (Sao Paulo State Government, 2017), there are quality standards and categories of use such as moderate and severe restrictions.

Regarding sewage sludge reuse, two national regulations (CONAMA 375/2006 and 380/2006) establish the criteria and requirements for agricultural use of sewage sludge and other derived products. Some of the requirements relate to environmental permission, specific treatment processes and criteria for frequent monitoring of the sewage sludge products (biosolids) depending on the specificities of agricultural application. The analysis of several parameters is mandatory including inorganic substances (heavy metals such as mercury, lead, arsenic and copper), pathogens (thermotolerant coliforms, helminth eggs, *Salmonella* spp. and viruses) and organic substances (chlorinated benzenes and non-chlorinated phenols). This regulation also defines the crops that can be cultivated in soil where the sludge will be applied, and restrictions of application for some specific sites such as preservation of natural areas (National Environmental Council, 2006b, 2006c). Currently, there are discussions on proposals to update these regulations, including the flexibilization of some requirements. In the present survey, these regulations were mentioned by some of the managers as a barrier to reuse sewage sludge. For instance, some analyses that are required have high costs and technical limitations.

One factor that could be considered as a barrier to implementation of resource recovery (De Boer et al., 2018) is the mind-set of water boards (plant managers) and the perception of other stakeholders in wastewater management and the general public (Poortvliet et al., 2018). According to our results, few managers answered positively (17.5% of the total of plants) about their interest in future initiatives of resource recovery. This finding raises the need for awareness about the benefits and importance of resource recovery to increase the interest of stakeholders, and consequently encourage implementation.

Another aspect that varied between the surveyed plants of our case study was the legal nature of the service provider. In the region of Sao Paulo, wastewater treatment management is the responsibility of the municipalities. The legal status of service providers can be divided into the following categories: private company, private right with public administration, public right/autarchy (absolute rule) and public-private partnership. Considering just the management of plant groups that perform resource recovery, the distribution of them according to service providers is as follows: 27 public-private partnerships, 5 private, 2 public right with private administration and 2 public right/autarchy. This indicates that the type of service provider does not seem to be a factor that influences resource recovery implementation since most of the plants (64% of the total of 143) in the Macrometropolis of Sao Paulo are managed by SABESP (public-private partnership).

3.4. Improvement options for resource recovery in the macrometropolis of Sao Paulo

Our results indicate that most of the evaluated regional plants are not operating at their maximum capacity, and some recently started their operation, which indicates that they can treat a higher volume of wastewater. This represents an opportunity to implement resource recovery actions in parallel to the expansion of wastewater treatment.

In the study area (Macrometropolis of Sao Paulo), the total volume of sewage generated is in the range between 39,885 and 59,238 L/s, considering the data of average water consumption per person per day (SABESP, 2018a), total population data (EMPLASA, 2019) and quantitative information provided by SNIRH (2013). The most populous metropolitan region (MRSP) contributes to 58.4% of the total flow. The other regions provide flow proportions as follows: MRPVNC 12%, MRC 8.9%, MRS 6.3%, MRBS 6%, UAP 5%, UAJ 2.3% and RUB 1.1% (SNIRH, 2013).

Considering the total of 143 surveyed plants, the approximate quantity of wastewater treated per year is 992 million m^3. This total volume contains resources that could be recovered, and some options will be presented below. The corresponding real value is certainly even higher, because it does not include all plants in the region, and the volume of sewage, which is not treated or not collected and treated. Based on the data from SNIRH (2013), the average index without collection and treatment was 13%, and the total sewage flow rate without collection and deprived of treatment was 6.8 m^3/s for the region.

In addition, based on data from SNIS (2019a), the authors calculated that the total collected sewage was 1.44 billion m^3/year and the total treated proportion was 1.06 billion m^3/year for the region in 2017. This indicates that about 26% of the collected sewage is not treated and several municipalities still do not have treatment for their collected sewage. Based on the estimate of total sewage generation in comparison with the total collected and treated wastewater (SNIRH, 2013), it can be estimated that around 70.3% of generated wastewater is collected and treated. With the future expansion of sanitation services in this area, resource recovery technologies could be integrated in the treatment systems.

In terms of urban and rural population, from the total municipalities (174) in the study region, most of them (162) are predominantly urban (urban population higher than 50%), of which 144 municipalities have an urban population higher than 75%. There are 3 municipalities that have the same proportion (50% rural and 50% urban) and only 9 municipalities have a higher rural population (IBGE, 2010). In developing countries, wastewater management is usually worse in secondary cities than in capital and large cities (Coulibaly et al., 2016). The sanitation issues (lack of proper sewage collection and treatment) are more accentuated in secondary cities, since governments prioritise major cities, which attract most of the economic activity (Coulibaly et al., 2016). The results of this study show that rural municipalities and the group with the same proportion (of rural and urban) have lower collection of wastewater (63.2%) and lower treatment (62.7% of the treated sewage) proportions than the urban municipalities (73.7% of collection and 74.6% of treatment) according to SNIS (2019b). Another finding was that all the surveyed plants with resource recovery are in urban municipalities. So, there is an opportunity to expand wastewater treatment particularly in rural municipalities integrated with resource recovery strategies.

Among the metropolitan regions, the MRSP is the one with the highest flow of untreated and not collected sewage (4615.8 L/s), followed by MRPVNC (1218 L/s), MRBS (466.1 L/s) and MRS (347.6 L/s) (SNIRH, 2013). The three first regions (MRSP, MRPVNC and MRBS) have a higher index without collection and treatment; 21.2%, 15% and 15%, respectively (SNIRH, 2013). In terms of access to sewage collection, MRSP is the region with the lowest percentage (58.5%) of which 56% is treated, followed by RUB with 59.7% and 68.5%, respectively. The other metropolitan regions have a sewage collection proportion and treatment percentage higher than 70% (SNIS, 2019b).

Considering the results of this case study, the most adopted treatment technology in the study region is activated sludge, followed by pond systems and anaerobic reactors (Table 1). The treatment process types for the 37 plants in the group with resource recovery solutions are distributed as follows: 25 plants with activated sludge, 7 with anaerobic reactors, 3 with other systems and 2 with pond systems. In general, the authors did not notice that the presence of resource recovery action is dependent on treatment technologies.

Depending on the wastewater treatment works, the recovery technology could be introduced in a way that it fits with the existing configuration of treatment units (Sarvajayakesavalu et al., 2018). Therefore, the existing treatment configuration can be an important aspect to be considered for planning purposes.

Anaerobic treatment processes (e.g., up-flow anaerobic sludge blanket, anaerobic membrane bioreactor and anaerobic digestion of sludge) are some technologies used for energy and valuable biochemical recovery (Akyol et al., 2019). However, in some of the plants with anaerobic processes, the low volume of biogas was reported by some managers as the reason for not performing recovery actions. One alternative would be to include other organic waste such as food waste into the anaerobic treatment process of sewage sludge, which may increase biogas production, and consequently the generation of heat or energy (Tolksdorf and Cornel, 2017). Co-digestion raises the concentration of methane in the biogas, and the biogas production increased by 25%–50% with the addition of 1%–5% food manufacturing and processing wastes to sewage sludge (Zahan et al., 2016). In some cases, the combined use of biogas from wastewater treatment plants and from sanitary landfills is also an option with great potential, as explored by Santos et al. (2018) within the Brazilian context. Other options for energy recovery such as heat pumps are not commonly applied worldwide (Kretschmer et al., 2016).

Considering that pond treatment was commonly applied in the study area, one possibility that could be evaluated for implementation is microalgae growth technology to make use of the existing infrastructure within these plants. The application of microalgae in open pond systems can offer many advantages such as the reduction of energy consumption (through aeration), improvement of the effluent quality, biomass harvesting for production of biofuel, food supplements and green pharmaceuticals (Craggs et al., 2014). The microalgae harvested can be used as a co-substrate together with primary sludge and waste activated sludge in anaerobic digestion for biogas production (Olsson et al., 2018). The biomass could be transported to larger plants equipped with digesters. Such initiatives are particularly interesting for developing and/or tropical countries, which can reduce their wastewater treatment costs via the recovery of their resources.

Raceway ponds, photobioreactors and hybrid systems of microalgae can be applied as a complement to existing wastewater treatment systems (Christenson and Sims, 2011). This is especially interesting for existing systems with aerated ponds, because of oxygen production by microalgae that reduce energy consumption. This technology is being applied to the side streams such as the reject water from digesters or the excess water from dewatering of digested sludge due to their high nutrient concentrations (Marazzi et al., 2019). As the reject water has a high temperature, it could be diluted to allow for a more optimal temperature supporting microalgae growth. Other sustainable adaptations that could be made to the ponds are floating macrophyte systems with the ability to produce nutrient-enriched plants simultaneously with wastewater treatment.

The treatment processes grouped under "others" in Table 1 require some further explanations. There are two plants using the Nereda process. This technology can recover valuable biopolymers, because aerobic granular sludge contains alginate-like exopolysaccharides, which can be harvested/extracted for economic applications in the food, paper, medical and construction industries (Van der Roest et al., 2015; Royal Haskoning DHV, 2017; Leeuwen et al., 2018). Thus, combining alginate extraction with existing excess sludge treatment processes has been the focus of some recent research (Van der Roest et al., 2015). In addition, as the Nereda process removes high proportions of phosphorus, consequently it allows for extra phosphorus recovery as struvite (Van Der Hoek et al., 2016). Another plant within the "others" group has a bioreactor with ultrafiltration membranes, which produces high-quality effluent that can be reused for several purposes including potable use (Yin and Xagoraraki, 2014). However, for developing countries, economic indicators still have a high weight in decision-making processes (Kalderis et al., 2010; Ngan et al., 2019).

The performances of the WWTP may be very variable and depend on the treatment processes, operational conditions and other factors. For the region of Sao Paulo (Macrometropolis), considering the BOD load of the total sewage volume, which is collected and treated, and the BOD load of the effluent discharged to the receiving surface waters, the estimated BOD removal efficiencies of the plants were around 83% (SNIRH, 2013). For example, a plant with an activated sludge process (the most common treatment process in the study area) unit is located in Sao Paulo city. This plant had mean removal efficiencies of 85.7% for COD, 24.5% for total N and 73.5% for total P (SABESP, 2018b). Oliveira and Von Sperling (2005) evaluated the performances of plants comprising several different technologies. These plants are located in Sao Paulo State and Minas Gerais State. For the activated sludge process, the removal efficiencies were higher: 85% (BOD), 81% (COD), 76% (TSS), 50% (NTK) and 46% (TP).

Other treatment processes commonly found in the study area are the up-flow anaerobic sludge blanket (UASB) and pond systems. According to Oliveira and Von Sperling (2005), the removal efficiencies for facultative ponds and anaerobic ponds followed by facultative ponds were 75% and 82% (BOD), 55% and 71% (COD), 48% and 62% (TSS), 38% and 45% (NTK), and 46% and 36% (TP), respectively. Moreover, for UASB systems without and with post treatment, the removal efficiencies were 72 and 88% (BOD), 59 and 77% (COD), 67 and 82% (TSS), −13 and 24% (NTK), −1. and 23% (TP), correspondingly.

Water reuse in cities is an important strategy to address current water shortage and quality challenges (Sun et al., 2016). However, the final water quality has to follow the regulation January 2017 (Sao Paulo State Government, 2017). Therefore, operational plant improvements might be required to uphold the regulation.

The water demand in São Paulo region is about 223 m^3/s distributed in household supply (48.95%), industry (31.32%) and agricultural irrigation (19.73%) (Sao Paulo State et al., 2013). Considering the average water consumption per person (128 L/day based on SABESP (2018a)) and the population of the region of Sao Paulo (Senese Neto, 2018), the total water demand for supplying households is around 4.3 million m^3/day. It is worth highlighting that about 49% of the total water demand is associated with the Alto Tiete river basin, which comprises 87% of the municipalities of MRSP (Sao Paulo State et al., 2013).

The potential of water reuse for industrial purposes was identified in a forecast for 2035 by the Master Plan for Water Resources Use in Sao Paulo Macrometropolis (Sao Paulo State et al., 2013). Mairiporã was the only city classified as having a "very high potential" for water reuse in the future. The other eleven municipalities were classified as "high potential"; all of them belong to the Piracicaba/Capivari/Jundiaí Basin indicating a deficit for industrial water supply. All treated wastewater could be directed to supply part of the industrial demand in these cities, especially Paulínia and Limeira. Based on the results from the survey presented in this paper, there is only one wastewater treatment plant that produces water for external reuse in this basin. Several other municipalities, including some in other metropolitan regions, were

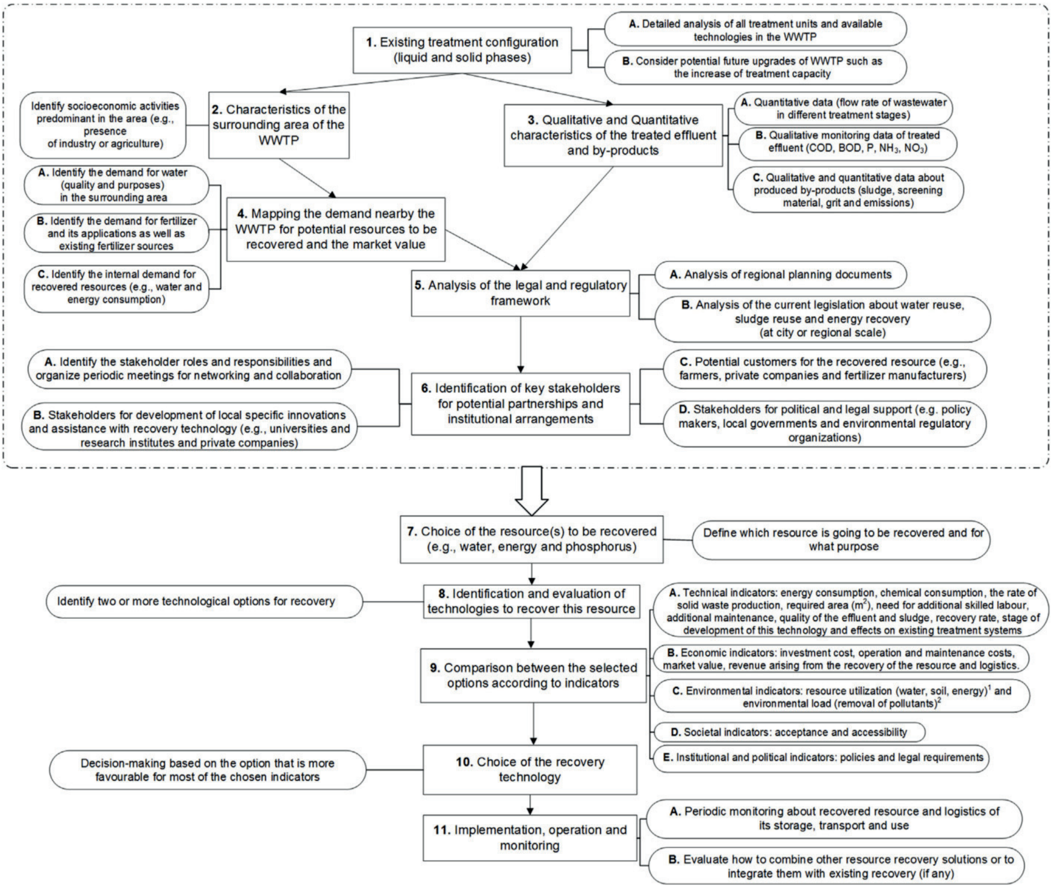

Fig. 4. Framework to guide decision-making on resource recovery for water and sanitation service providers. Notes: [1] It is also a technical indicator; and [2] The environmental load includes pollutants (nutrients and organic matter) measured through the removal efficiencies of biological oxygen demand (BOD), chemical oxygen demand (COD), ammonia (NH_3), nitrate (NO_3) and phosphorus (P).

classified as having a "medium potential". There are cities classified as having a "medium potential" in the megacity of Sao Paulo (e.g., Guarulhos, Embu and Mauá), Piracicaba Agglomeration and Sorocaba region (Sao Paulo State et al., 2013).

The agriculture sector also requires a lot of water. The water demand for irrigation in agriculture will increase by 33, 31 and 10% in Tietê and Sorocaba, Piracicaba/Capivari/Jundiaí and Mogi-Guaçu water resources management units, respectively, by the year 2035. Based on this forecast, there are several municipalities, which are likely to face water scarcity challenges. Furthermore, the public water supply demand is also likely to increase according to the projections, especially in the water resources management units of Alto Tietê, Piracicaba Capivari Jundiaí, Baixada Santista and Tietê/Sorocaba (Sao Paulo State et al., 2013).

Nutrient recovery is especially interesting for municipalities that have agriculture as the main economic activity. The predominant economic activity of the municipalities was assessed based on data from The Brazilian Institute of Geography and Statistics (IBGE, 2016). There are five relevant municipalities in the Macrometropolis of Sao Paulo; most of them are located in the Metropolitan Region of Sorocaba. Furthermore, there are 14 other municipalities where agriculture is the second or third main economic activity in terms of importance. If the wastewater treatment facilities in these cities or nearby ones apply nutrient recovery techniques from wastewater treatment, this activity could also benefit them as an alternative fertilizer source.

Some measures of resource recovery compete with each other. Therefore, it is necessary to prioritise. In this context, the value pyramid is a tool that allows for the distinction between the recovered products and can support the decision. According to this tool, the hierarchy from low to high value is as follows: energy (electricity and heat), transportation fuels, materials and chemicals (e.g., fertilizers), food, and health and lifestyle (e.g., pharmaceuticals and fine chemicals) (Van Der Hoek et al., 2016; Betaprocess Bioenergy, 2019). Moreover, the framework proposed by the authors in the next section is a tool facilitating further decision-making.

3.5. Framework for resource recovery planning and implementation

In most urban areas within developing countries, there is no effective system for collection and treatment of wastewater, which causes eutrophication and other water pollution issues. The lack of both infrastructure and a legislative framework for the new treatment processes further intensifies this challenge, and poor incentives can be considered as the reason for low resource recovery implementation (Sarvajayakesavalu et al., 2018). Moreover, these areas face the overall challenge of the use of natural and financial resources in a sustainable manner (Woltersdorf et al., 2018).

Informal urban settlements lack infrastructure entirely, and could be the first to adopt new sustainable and cost-effective treatment systems (Mega-Cities Project, 2019). In the case of resource recovery implementation, there is an opportunity to implement these solutions in the megacities of developing countries. These areas need to expand the coverage of wastewater treatment through building new wastewater treatment plants or retrofitting the existing ones.

Public acceptance is an important challenge, since low-income communities do not want to have “second class” solutions (Mega-Cities Project, 2019). For instance, public perception is commonly an important barrier to implementation of water reuse. For example, low public acceptance for water reuse might be attributed to the lack of information such as evidence demonstrating the technological success and safety for public health (Wilcox et al., 2016).

The selection of an appropriate method is a challenge as it is highly site-dependant. It follows that the regional water quality and influent quantity, size of the treatment plant and other economic considerations play a major part in the selection procedure.

In order to accelerate the process of resource recovery implementation, several complex aspects should be considered. Therefore, the authors created a framework (Fig. 4) to support the planning process and encompass a set of measures to contribute to decision-making.

The proposed framework contains several steps and can work as an action plan to achieve resource recovery implementation. The qualitative and quantitative characteristics of the influent vary in different regions of a country (Sun et al., 2016), and this should be considered for evaluating the effluent for reuse. When mapping the demand, it is useful to analyse regional planning documents. Each city has a different context and a specific demand of what resource is more important to recover from the wastewater treatment plant. According to Günther et al. (2018), plant managers can choose from a wide range of techniques to decide which of them is more appropriate and fits better to local raw material availability, economic and ecological boundary conditions.

For the framework step 9, which is concerned with a comparison between the selected recovery options, some indicators were proposed. This comparison between the recovery methods allows for the discussion of their advantages and disadvantages, considering the option that best adjusts the economic-technical-environmental tripod, facilitating decision-making. This framework could be integrated into the plans of wastewater treatment companies to base strategies of resource recovery at municipal and regional levels. It is expected that the framework is flexible and can be adapted by users, depending on the context (e.g., plant size and specific demand) and available data. Besides supporting retrofitting of resource recovery solutions for existing treatment facilities, the framework can also be applied for new plants at the planning stage.

The expected benefits from a successful implementation of the proposed framework are (a) the reduction in time for decision-making of resource recovery projects; (b) lowering of adverse environmental impacts related to wastewater treatment processes through improvement of effluent quality, reduction of energy consumption and allowance for more efficient natural resources management; (c) contribution to water conservation providing economic benefits by generation of revenues of recovered products; and (d) saving money from operational costs related to, for example, by-product management and disposal as well as energy consumption.

3.6. Comparison of the region of Sao Paulo with other megacities in developing countries

This comparison complements the discussion and contextualizes original results with the literature. Treatment technologies are usually basic in developing economies of the Brazil, Russia, India, China and South Africa (BRICS) group. For example, in Russia, wastewater treatment facilities have a similar configuration compared to the region of Sao Paulo, consisting of preliminary treatment units such as screens and grit chambers.

The wastewater of Moscow City is treated at the Kuryanovskaya and Luberetskaya secondary biological treatment plants, which discharge treated effluents to the Moscow River downstream of the city. In some plants, the wastewater inflow rate is between 10,000 and 100,000 m^3/day. The sludge for these works is only reused for composting after the digestion tank and the mechanical sludge dewatering room. In larger plants with an inflow rate higher than 100,000 m^3/day, digestion gases are also recovered benefitting a mini-thermal power plant (MosvodokanalNIIproject Institute, 2015). After biogas purification, the mini-thermal power plant produces electricity and additional heat to supply a central heat-supply station. This form of energy recovery can improve the energy efficiency of these plants and reduce greenhouse gas emissions (MosvodokanalNIIproject Institute, 2015).

In Johannesburg, South Africa, there is a need for policy change and implementation to promote the reduction, reuse and recycling of phosphate as well as to control pollution. The wastewater treatment capacity is insufficient in South Africa for the treatment of all wastewater types. This causes pollution both from untreated wastewater and from treated effluents, which do not meet standards and might cause microbial contamination, particularly due to the rapid urbanization of informal settlements located near cities (Food and Agriculture Organization of the United Nations (FAO), 2016). Policies could be updated to promote the reduction, reuse and recycling of phosphate. Consequently, this would mitigate the pollution challenge. Regarding phosphorus recovery, struvite processes were shown to be unprofitable, partly due to low struvite prices, which are subject to relatively low regional South African phosphate fertilizer market prices (Sikosana et al., 2017). As such, fertilizer policy and price regulations would help to improve the placement of struvite in the fertilizer market and to increase fertilizer prices to values more comparable to the global market (Sikosana et al., 2017).

In China, the mostly adopted treatment technologies in municipal plants are oxidation ditches (30.5%), anaerobic-anoxic-oxic processes (16.2%), conventional activated sludge systems (10.0%), anaerobic-oxic processes (8.2%) and sequencing batch reactors (6.8%) (Sun et al., 2016). Thus, the analysis of each context is important to assess the potential for resource recovery strategies. There is some resource recovery from municipal wastewater in some regions, but the proportion of resources utilization after treatment is low. According to Zhang et al. (2016), who studied 656 WWTP in 70 cities of 7 Chinese regions, the proportion of resource recycling (recycled building materials and compost) is only 25%. Approximately 15% of wastewater is inefficiently treated, and the water reuse from treated effluent is low. Another concern is that up to 40% of sewage sludge is still improperly disposed of (Lu et al., 2019). In addition, the operation ratio of the treatment plants is below the design capacity due to insufficient sewer networks (Lu et al., 2019).

Sun et al. (2016) estimated the recovered resources from wastewater in China: water reuse of 3.76×10^9 m^3/year, NH_3–N recycling of 2.05×10^5 tons/year and total phosphorus recovery of 2.92×10^4 tons/year (Sun et al., 2016). The water reuse rate in some megacities in China has reached 35–60%, and provinces with low available water resources and high gross domestic product (GDP) levels showed larger proportions of reclaimed water construction and utilization (Chen et al., 2017). Thus, the calculated potential for recovery of water, nutrients and organics from wastewater at national scale is much higher (Sun et al., 2016).

Regarding energy recovery, there is a large wastewater treatment plant with a population equivalent of 3.5 million in Shanghai recovering energy from biogas to meet the heat demand of both digesters and sludge thermal drying processes. The remaining biogas is burned (Zhao et al., 2019).

Resource recovery measures are not commonly implemented in wastewater treatment plants in developing countries, so studies supporting the planning of more recovery practices are important.

Potential multiple societal benefits linked to resource recovery should be highlighted to attract more investment from new sectors such as agriculture (Andersson et al., 2018). For example, in countries with strong agricultural activity, there is an opportunity to develop a biofertilizer market model resulting from anaerobic digestion (Felca et al., 2018; Battista et al., 2019) or other nutrient recovery solutions from their wastewater treatment plants, benefitting both rural and urban communities.

3.7. Study limitations

Some wastewater treatment organizations did not answer the questionnaire, which limits the interpretation of findings. Also, in some municipalities with a high number of wastewater treatment plants and/or insufficient staffing resources, it was not possible to collect data from all plants. Another limitation was that few responses concerning less important data were incomplete. Furthermore, some plant managers were temporarily unavailable, which led to a pre-longed period (July 2017 to April 2019) of data return.

4. Conclusions and recommendations

This study was undertaken to increase the evidence base of resource recovery options by providing accurate and relevant data from wastewater treatment plants and their resource recovery levels in the most populous area in South America; the region of Sao Paulo. These data should support the planning of various resource recovery projects in the region: water reuse, biofertilizer production and energy recovery initiatives based on local socio-economic activities and regional demand, contributing to long-term sustainable water management in urban areas.

The results show that there is currently low implementation of resource recovery in the region, but there is a great potential to expand the strategies of resource recovery, either for new plants or for retrofitting existing ones. The predominant recovery action is internal water reuse while other options have not been much explored. Another finding is that recovery is concentrated mainly in large- and medium-sized plants. However, there are more small plants in the studied region, so it is important to evaluate how to expand the recovery solutions to these small plants as well.

For most of the studied works, the sludge generated is disposed in landfills. In dense large cities, there is no space available for this, which involves additional costs for wastewater treatment facilities. So, other options such as sludge reuse are very promising. One factor that can help to support the implementation of such options is partnership with universities for new developments and with private companies for implementation as shown for sludge reuse cases. In addition, results can facilitate the identification and evaluation of the regional demands for which resources can be recovered; e.g., fertilizer or water for reuse, and the identification of priority areas in each metropolitan area that comprises the region of Sao Paulo.

Most of the addressed megacities in developing countries have low implementation of resource recovery and poor management and operational conditions for their wastewater treatment facilities. Incentive-based policies are important to stimulate the interest of water utilities on implementation of resource recovery technologies and to support the introduction of recovered products in the market. According to some of the managers, some barriers for sludge reuse implementation are the lack of government incentives and legislation. These are thus interesting aspects for future studies.

This study also offers several further research possibilities. Specifically, the detailed data obtained for the region of Sao Paulo could be compared with data from other urban agglomerations to establish a global inventory. Further studies involving life-cycle assessments are recommended, particularly for the evaluation of environmental impacts related to resource recovery options. Moreover, they could be combined with the framework application. Our contribution can be useful for decision-makers applying the same procedures as proposed in this study to other cities and regions with similar conditions. Also, countries with different conditions from the ones described in this study might benefit from the proposed assessments. The proposed framework has been designed for application in similar case studies. However, further studies are encouraged to validate its potential.

Author contribution

Mariana Cardoso Chrispim – Conceptualization, Methodology, Investigation, Formal analysis, framework creation, Visualization, Writing - original draft, writing-review & editing. Miklas Scholz –; Conceptualization, Writing - review & editing, Supervision. Marcelo Antunes Nolasco –; Project administration, Writing - review & editing, Supervision.

Declaration of competing interest

There are no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.109745.

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Supplementary material 1: Questionnaire

This material outlines the questionnaire filled-in by managers of wastewater treatment plants.

- Type of plant (treatment unit) including configuration and flow chart of treatment processes: Water line (effluent) and solid line (sludge)
- Presence of industrial wastewater (% of total)
- Population equivalent (number of inhabitants)
- Current raw wastewater inflow rate (m^3/day) and a specification of the period for these data
- Initial strategy regarding recovery of some types of resource (e.g., biogas, reuse water and sludge as fertilizer)
- Retrofitting of resource recovery options
- Description of intentions and initiatives (with timings) to recover resources
- Table SM1 on material and energy

Table SM1. Material and energy for the water and sludge treatment lines as well as other forms of recovery (partly after Papa et al. (2017)).

Material	Energy
Water treatment line	
• Solid waste from pre-treatment • Grit (specify destination) • Screening of material (destination) • Oils and grease (destination) • Treated effluent (reclaimed water) for external purposes; Volume/month; Destination • Treated Effluent for internal purposes (volume/month and destination) • Others	• Energy recovery specifications for the plant (e.g., use of biogas from anaerobic reactor, heat recovery and others)
Sludge treatment line	
• Sludge reuse actions such as soil conditioner, compost or incineration • Bio-fuel production • Nutrient recovery • Others	• Energy recovery from biogas (thermal or electrical energy) • Enhancement of biogas production (e.g., co-digestion with solid waste from food or gardening) • Others
Other forms of recovery	
• Engine/machine waste oils • Recovery of chemical products for phosphorus precipitation • Recovery of organic matter for denitrification enhancement • Others	• Energy production from other renewable sources (e.g., photovoltaic systems and wind turbines) • Recovery of heat produced by blowers/pumping systems • Others

Supplementary material 2: Resource recovery implementation

The situation of wastewater treatment plants regarding resource recovery implementation in the region of the Macrometropolis of Sao Paulo is shown in Figure SM2.

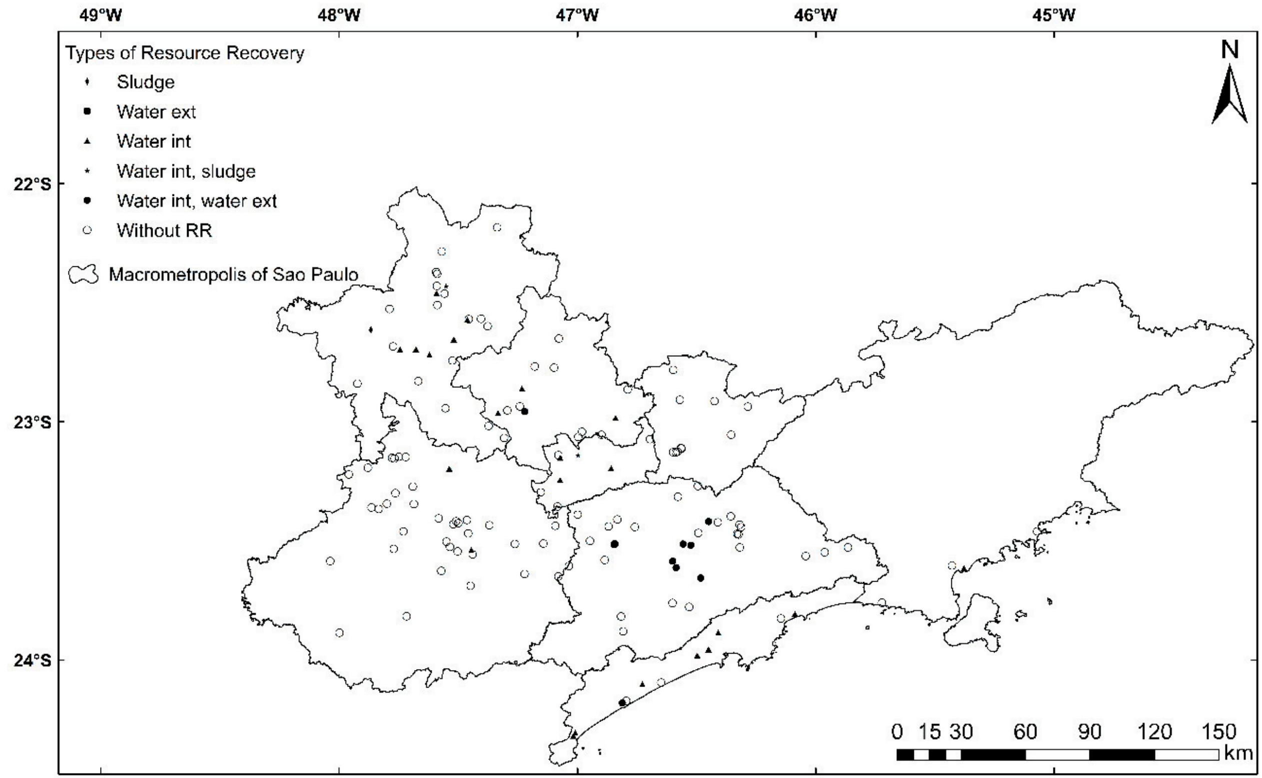

Fig. SM2. Resource recovery implementation overview. Notes: Sludge, plant with sludge recycling; Water ext., external water reuse; water int., internal water reuse; water int., sludge, plant with internal water reuse and sludge recycling; water int., water ext., plant with internal and external water reuse; RR, resource recovery.

Supplementary material 3: Distribution of wastewater treatment plant size

Figure SM3 shows the distribution of wastewater treatment plant sizes and the corresponding inflow rates in the region of the Macrometropolis of Sao Paulo.

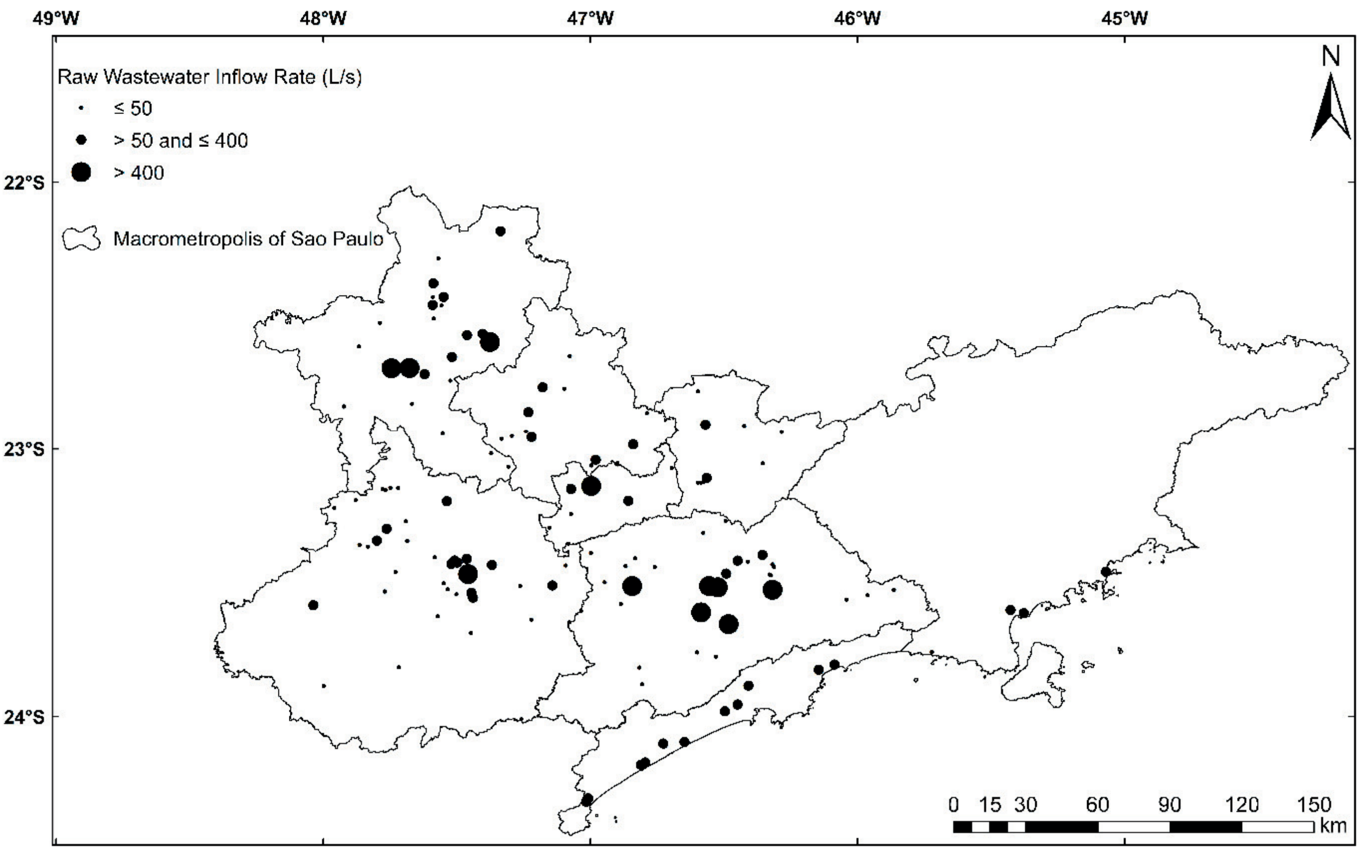

Fig. SM3. Distribution of wastewater treatment plant size.

Supplementary material 4

Table SM4. Raw data for surveyed plants (plant names are confidential).

Municipality	Size	Resource recovery	Type of recovery	Recovered amount (m^3/month) of internal water reuse	Recovered amount (m^3/month) for external water reuse	Raw wastewater inflow rate (L/s)
Águas de São Pedro	small	yes	sludge			2
Alumínio	small	no				13.24
Araçariguama	small	no				6.6
Arujá	medium	no				93.76
Atibaia	small	no				1.6
Atibaia	small	no				4.54
Atibaia	small	no				6.51
Atibaia	small	no				9
Atibaia	medium	no				150.46
Barueri	small	no				2.5
Barueri	large	yes	water ext		1,814.40	10,843
Bertioga	medium	yes	water int			63.9
Bertioga	medium	no				91.6
Biritiba Mirim	small	no				29.6
Boituva	small	no				10.46
Boituva	medium	no				54.12
Bragança Paulista	medium	no				210.13
Cabreúva	small	no				0.5
Cabreúva	small	no				7
Cabreúva	small	yes	water int	14,773.50		38
Cajamar	small	no				0.28
Campinas	medium	yes	water int, water ext.	5,200	340	256.63

Campo Limpo Paulista e Varzea Paulista	medium	yes	water int	87404.4		281
Capela do Alto	small	no				0.79
Capela do Alto	small	no				13.74
Caraguatatuba	small	no				125
Caraguatatuba	medium	yes	water int			220
Cerquilho	small	no				6.9
Cerquilho	small	no				11
Cerquilho	small	no				41.2
Cerquilho	small	no				41.2
Cesário Lange	small	no				2.6
Cesário Lange	small	no				13.97
Charqueada	small	no				19
Cotia	small	no				47.88
Cubatão	medium	yes	water int	300		84.5
Cubatão	medium	yes	water int	150		131.8
Elias Fausto	small	no				4.3
Elias Fausto	small	no				16
Embu-guaçu	small	no				14.71
Embu-guaçu	small	no				18.87
Guarujá	medium	yes	water int			234.14
Guarulhos	small	no				16
Guarulhos	medium	yes	water int, water ext		2,592	70.00
Guarulhos	medium	no				70
Holambra	small	no				27.2
Hortolândia	medium	yes	water int	3,402		315
Ibiúna	small	no				24.1

Iperó	small	no				4.06
Iperó	small	no				16.7
Itanhaem	medium	yes	water int, water ext	80	320	79.3
Itanhaem	medium	no				178.5
Itapetininga	medium	no				191.5
Itaquaquecetuba	small	no				0.3
Itaquaquecetuba	small	no				4.32
Itaquaquecetuba	small	no				12.19
Itaquaquecetuba	small	no				13.19
Itatiba	small	no				0.9
Itatiba	medium	yes	water int	1,522		141
Itupeva	small	no				9.8
Itupeva	medium	yes	water int	22,549		58
Jarinu	small	no				8
Joanópolis	small	no				11.15
Jundiaí	large	yes	water int, sludge	1100		1133.44
Leme	medium	no				353.6
Limeira	small	no				2.7
Limeira	medium	no				75
Limeira	medium	yes	water int	560		76
Limeira	large	no				438
Mairiporã	small	no				33.43
Mauá	large	yes	water int, water ext	195.15	375.5	481.83
Mombuca	small	no				4
Mongagua	medium	no				69.5
Mongagua	medium	yes	water int	80		178.7
Monte Mor	small	no				4.2

Monte Mor	small	no			22
Monte Mor	small	yes	water int	442.8	41
Morungaba	small	no			15
Nazaré Paulista	small	no			5.06
Paulínia	small	no			7.9
Paulínia	medium	no			148
Peruíbe	medium	yes	water int	80	57.8
Peruíbe	medium	yes	water int	80	237.1
Piedade	small	no			24.28
Pilar do Sul	small	no			24.1
Pinhalzinho	small	no			7.73
Piracaia	small	no			26.35
Piracicaba	small	no			5
Piracicaba	small	no			12
Piracicaba	small	no			30
Piracicaba	small	yes	water int	64,800	67.5
Piracicaba	medium	yes	water int	64,800	357
Piracicaba	medium	yes	water int	64,800	413
Piracicaba	**large**	yes	water int	64,800	436
Pirapora do Bom Jesus	small	no			2.41
Porto Feliz	medium	yes	water int	150	95
Rio Claro	small	no			2
Rio Claro	small	no			3
Rio Claro	small	no			6.3
Rio Claro	small	no			10
Rio Claro	small	no			14
Rio Claro	medium	no			85
Rio Claro	medium	yes	water int, sludge		155

Rio Claro	medium	yes	water int			254
Salesópolis	small	no				1.37
Salesópolis	small	no				13
Saltinho	small	no				12.5
Salto de Pirapora	small	no				44.11
Santa Gertrudes	small	no				33.6
Santana de Parnaíba	small	no				1.78
São Bernardo do campo	small	no				4.35
São Bernardo do campo	small	no				12.8
São Miguel Arcanjo	small	no				22.1
São Paulo	small	no				2
São Paulo	medium	yes	water int, water ext	7,225	40,444	49.64
São Paulo	large	yes	water int, water ext		7,257.60	992.9
São Paulo	large	yes	water int, water ext		1,044,576	2,483
São Paulo	large	yes	water int, water ext		78,796.80	2,573.60
São Roque	small	no				0.1
São Roque	medium	no				61.34
São Sebastião	small	no				45
São Vicente	medium	yes	water int	100		53.8
São Vicente	medium	yes	water int	500		89.9
Sorocaba	small	no				2
Sorocaba	small	no				8
Sorocaba	medium	no				60
Sorocaba	medium	no				100

Sorocaba	medium	no		170
Sorocaba	medium	no		300
Sorocaba	medium	no		309
Sorocaba	large	yes	water int	700
Suzano	large	no		779.8
Tatuí	small	no		13.19
Tatuí	small	no		22.61
Tatuí	medium	no		94.13
Ubatuba	small	no		155.8
Vargem	small	no		3.91
Vargem Grande Paulista	small	no		9.44
Vinhedo	small	no		43.7
Vinhedo	medium	no		96.9
Votorantim	small	no		30
Votorantim	medium	no		90
Votorantim	medium	yes	water int	105

Water int., internal water reuse; sludge, sludge recycling; water ext., external water reuse.

Paper III

water

MDPI

Article

A Framework for Sustainable Planning and Decision-Making on Resource Recovery from Wastewater: Showcase for São Paulo Megacity

Mariana C. Chrispim [1,2], Fernanda de M. de Souza [2], Miklas Scholz [1,3,4,*] and Marcelo A. Nolasco [2]

1 Division of Water Resources Engineering, Faculty of Engineering, Lund University, John Ericssons väg 1, P.O. Box 118, 22100 Lund, Sweden; mariana.chrispim@usp.br
2 School of Arts, Sciences and Humanities, University of São Paulo, Arlindo Bettio Avenue 1000, São Paulo 03828-000, Brazil; fernanda.marco.souza@usp.br (F.d.M.d.S.); mnolasco@usp.br (M.A.N.)
3 Department of Civil Engineering Science, School of Civil Engineering and the Built Environment, University of Johannesburg, Kingsway Campus, P.O. Box 524, Auckland Park 2006, Johannesburg, South Africa
4 Civil Engineering Research Group, School of Science, Engineering and Environment, The University of Salford, Newton Building, Peel Park Campus, Salford M5 4WT, UK
* Correspondence: miklas.scholz@tvrl.lth.se; Tel.: +46-703-435-270

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Abstract: Currently, it is important to develop strategic frameworks to support the selection of sustainable resource recovery solutions. This study applies a new framework for planning, implementation, and assessment of resource recovery strategies for a full-scale wastewater treatment plant (WWTP) in São Paulo megacity. The framework comprises several steps based on case study-specific data and information from current literature. Data were collected from various sources: a survey with a wastewater treatment utility, national and regional databases, and review of local regulations and international literature. Treatment configuration, wastewater and by-products composition, potential demand (for water, energy, and phosphorus), stakeholder identification, and local legislation were thoroughly discussed regarding decision-making on resource recovery. Scenario analysis was used to explore suitable nutrient and energy recovery measures based on indicators. Biogas recovery and sewage sludge composting showed more favorable conditions due to similar experiences in the area and robust legislation. The proposed framework is a simplified tool, and its application can support managers to get information on resource recovery and how to plan such initiatives in easier ways to facilitate wiser decision-making, and better operation and management. The results on framework use and refinement can guide potential applications in other contexts and stimulate public policy formulation and further research.

Keywords: decision-support system; resource-oriented sanitation; sewage; integrated process; water–energy–food nexus; dense urban areas; developing countries; energy recovery

1. Introduction

The scarcity of natural resources is a driver for initiatives of resource recovery and reuse, by producing biogas, fertilizer, and water that can be returned to the market. Recovering valuable compounds of municipal wastewater includes several important aspects for the planning process, decision-making, and implementation.

Due to the increase of global urbanization, cities are special places for recovery of resources, and wastewater treatment plants (WWTP) are sites where such processes can take place. Wastewater treatment facilities are part of the cities' metabolism and the local region; thus, resource recovery processes should be planned in an integrated way. For instance, how the treatment plant could contribute with potential resources to the local industries clusters or agriculture. WWTP should be integrated within the local community and economic activities [1]. Thus, cities have great potential to support the progress towards regional sustainable development [2].

Sustainable Development Goal 11 focuses on making cities inclusive, safe, resilient, and sustainable, and with the inclusion of policies and plans towards resource efficiency, and by 2030, to reduce the adverse environmental impacts of cities with particular attention to waste management [3]. In this context, cities require efficient management of natural resources in the face of growing demands and changing environmental conditions [4].

The incorporation of resource recovery solutions (e.g., water reuse, nutrient and energy recovery) can improve the overall performance of WWTP [5] and contribute to the circular economy in wastewater treatment and urban sustainability [6]. The benefits provided by resource recovery implementation are higher in areas that face stress and low availability or high consumption of resources (e.g., water) [7]. Conservation of water resources should be a priority especially for megacities in developing countries, which face water shortages, water pollution, lack of infrastructure and public services, and a lack of provision of clean water and safe disposal of wastewater and stormwater [8,9]. Megacities, where large WWTP are usually in operation, can improve resource recovery with economic efficiency and profitability while generating environmental benefits such as improvement of surface water quality and mitigation of eutrophication issues [10,11].

However, there is an absence of studies on how to integrate resource recovery technologies in municipal wastewater treatment plants. Some current barriers to implementation of resource recovery from wastewater are: How to combine resource recovery solutions to maximize plant productivity [7,12,13]; and a lack of decision-making tools and methodologies to identify the best solution for each context [14,15]. Most literature on resource recovery focuses on the discussion of recovery processes and technologies and not on the interactions with environment and stakeholders (researchers, policymakers, and end-users) [16,17]. Therefore, an integrated approach of potential resource recovery solutions on a real scale is necessary [16] (Table 1).

Table 1. Identified knowledge gaps with key journal paper references and how these gaps are directly addressed by the present paper.

Knowledge Gaps	References of Previous Papers	How this Gap is Addressed in Our Paper
Great potential of application of resource recovery solutions in megacities; few studies on nutrient recovery in South American countries	[9–11,18]	The framework is applied to a representative WWTP in São Paulo megacity. Additionally, there is an indication of applicability to other megacities, considering resource scarcity and local characteristics. Nutrient recovery options are assessed.
Lack of studies that focus on interactions with local environment and stakeholders (integrated approach)	[16,17,19]	Linkages of sanitation with economic activity (market demand), social (stakeholders), and analysis from water–energy–nutrient nexus perspective (e.g., water consumption in the area).
Comparison of resource recovery strategies from systems' perspective and understanding of related impacts	[20]	Step 9 of the framework contains detailed comparison of different scenarios for energy and nutrient recovery.
Lack of tools and methodologies to identify the best solution to each context, to support planning and decision-making	[12–14]	The framework application allows the most suitable solution to be identified considering technical, environmental, societal, economic, and political/institutional indicators.
More comprehensive framework for planning, decision-making, and assessment of any kind of resource recovery action, including a large set of indicators and stakeholders' groups.	[21–24]	The proposed framework is tested in a real case: It is shown to be simple to apply and facilitates the planning process and the choice of the recovery technology. Nutrient and energy recovery scenarios are analyzed in detail.

Decision-making on urban water infrastructure projects is complex, since it should consider the interactions between infrastructure (e.g., technological options), environmental, institutional, economic, and social characteristics [19]. Several decision-making parameters can be evaluated to choose the optimum recovery technology such as costs (capital and operational expenditures), recovery rate (%), environmental impacts (heavy metals and organic contaminants), wastewater composition, and market for the recovered product (e.g., phosphate fertilizer) [25]. These parameters should be considered as early as possible, such as at the design stage [23].

Local context characteristics should be carefully examined and considered in the planning process for resource recovery [7,26]. Especially in developing countries, there is insufficient planning to include efficient sanitation systems [27]. Many technical options are available to recover resources from wastewater and sludge; however, some technologies might not be suitable for developing countries, because of the costs and requirements on treatment processes and energy demand [28].

Besides the costs, local legislation can also influence the selection of resource recovery measures [14]. In some cases, legislation can act as a barrier and changes are required, while in others legislation and standards can be drivers for resource recovery implementation. Then, identifying legal and institutional challenges related to resource recovery can assist in the planning of wastewater treatment plants to support strategic decisions.

It is important to develop strategic frameworks to support society (policymakers and general public) in the selection of resource recovery solutions, such as sustainable options for sewage sludge management [22,29]. According to Romeiko [20], it is necessary to compare environmental performances of resource recovery-based wastewater treatment plants to support the design and implementation of resource recovery strategies from system perspectives. This comparison can include several indicators. As a result, a better understanding of resource recovery technologies will allow for the design of future systems [30].

A proposed framework as a tool to stimulate/support planning and decision-making on resource recovery from wastewater treatment was presented by Chrispim et al. [31]. As the next step, this paper presents how this framework can be applied, offers significant suggestions for improvement, and addresses research gaps in the field (Table 1). The aim was to showcase the new framework for planning, implementation, and assessment of resource recovery strategies for a representative WWTP. The specific objectives were to apply all the steps of the proposed framework to support decision-making on resource recovery strategies; to recommend operational and technological strategies of resource recovery (nutrients and energy) to be applied in this representative facility, considering economic, technical, environmental, societal, and political indicators; and to identify strengths and potential improvements of the framework.

In this paper, the case study was a large WWTP in São Paulo megacity and the authors identified current practices and opportunities for improvement of this facility, including processes and technologies for resource recovery. Based on real data from a practice system, it was possible to propose innovations, and to support the implementation of new strategies and more effective solutions for resource recovery from wastewater. Understanding and testing the framework application was an important task to prioritize future data collection efforts.

The results could contribute to the creation of technical and scientific knowledge and a better understanding of planning, retrofitting, and upgrading of municipal WWTP with resource recovery, and to support the development of public policies or regional programs in this area. Wider applicability of the results for other cities is suggested for better wastewater management practices and for supporting resource recovery implementation. Through the framework application, it is possible to address what needs to change to achieve or optimize the resource recovery initiatives. Some key questions addressed in our paper are: What resources are available in the waste streams in the studied plant; what market demand there might be for them; how they could be recovered; what the linkages with local legislation are; and who the key stakeholders are.

2. Methods

2.1. Developed Framework

The methodology applied in this paper was based on a framework developed to support the planning and decision processes about resource recovery strategies in wastewater treatment plants [31]. In the cited paper, the framework was just outlined (briefly introduced). The present paper contains novel aspects: The first application in a real situation, suggestions of improvements and new arrangements of the framework, potential impact of its application in world's megacities, and estimation of potential resource recovery solutions for the study region. The framework (Figure 1) was applied in a case study of a wastewater treatment plant in the São Paulo megacity (or the metropolitan region of São Paulo). Wider applicability of the framework is suggested in Table 2.

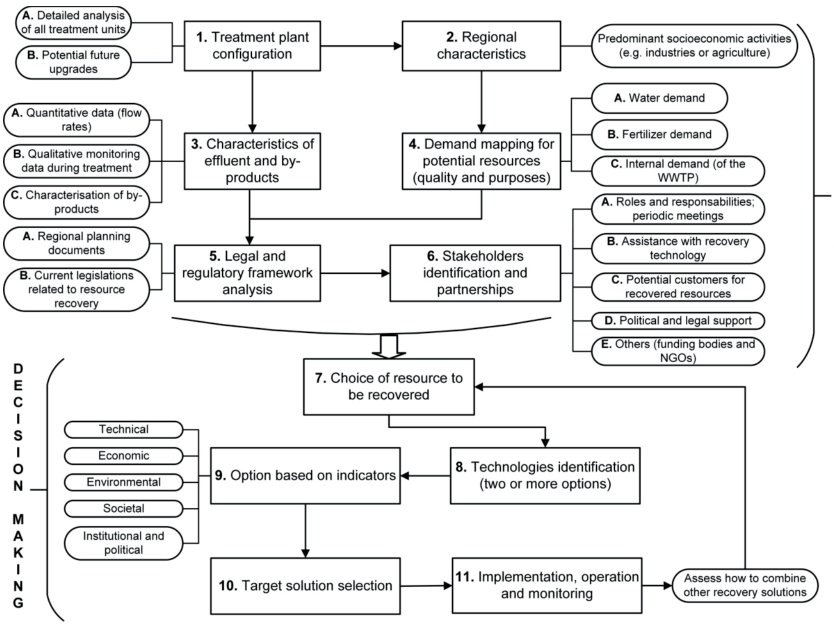

Figure 1. Framework applied in this study (adapted from [31]).

Table 2. Indication of the framework applicability in megacities similar to São Paulo (New York is shown for comparison purposes).

Megacity	Level of Applicability	Reliability Level	Similarity of Wastewater Treatment Characteristics	Demand for Potential Resources	Water Demand; Water Scarcity	Energy Demand	Phosphorus Demand	Expected Impact of Framework Application
São Paulo	high	high	high	high	high	high	medium	high
Mexico City	high	medium	high	high	high	high	medium	high
Johannesburg	high	medium	high	high	high	high	low	medium
Cairo	medium	medium	medium	medium	high	low	low	high
Chengdu	medium	low	low	medium	medium	high	low	medium
Shanghai	medium	low	medium	medium	high	medium	low	medium
Delhi	high	low	high	high	high	high	high	high
New York	low	medium	high	low	low	medium	low	low

Notes: Based on expert's judgement of the authors (after consulting with local experts in the area and urban sustainability indexes; Sustainable Cities Water Index [32], Blue City Index [33], and SDEWES Index [34]). The assessment considered not only the demand (and use) for water, energy, and phosphorus, but also if there has been an increase in the resource consumption (e.g., electricity), its current availability, and if it represents a key issue for the city. São Paulo, Mexico City, Cairo, and Delhi refer to their metropolitan areas, Johannesburg, Chengdu, and New York to urban agglomerations, and Shanghai is the city proper (based on classification from the United Nations [35]).

2.2. Studied WWTP

The information regarding the plant was gathered with the support of the São Paulo State Water Supply and Sewerage Company (SABESP), who owns and operates this facility. The wastewater treatment plant ABC is located in São Paulo city (23°36′41.58′′ S and 46°35′9.24′′ W) (Figure 2). This facility treats sewage from six cities, totalizing an approximate population equivalent of 1.4 million inhabitants.

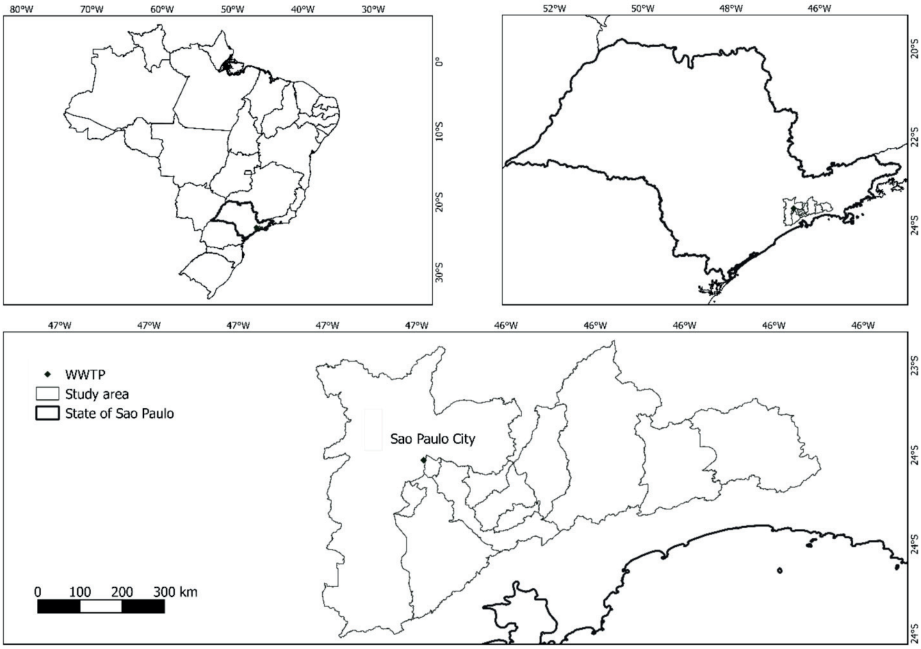

Figure 2. Map of the study area.

This plant started up in 1998, with a maximum treatment capacity of 3 m^3/s, and it is foreseen to increase this capacity (Section 3.1.1). The mean wastewater inflow rate was 2.33 m^3/s during the analyzed period (07/2016 to 06/2017). The treatment processes for liquid and solid phases are illustrated in Figure 3. A detailed description of treatment stages is given in Section 3.1.1. Detailed information about the study area is presented in Section 3.1.2.

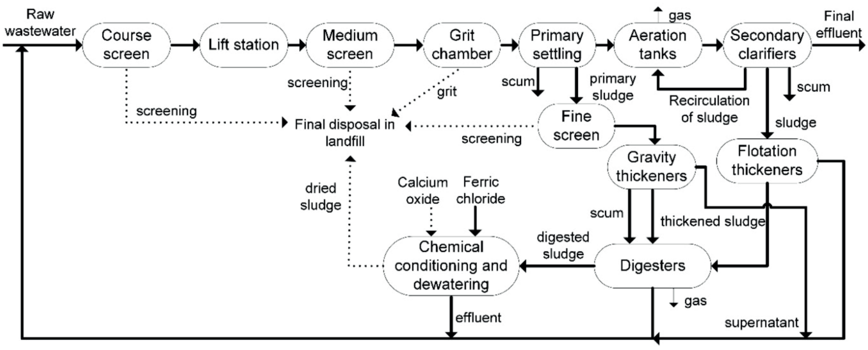

Figure 3. Diagram of the wastewater treatment plant ABC with all the treatment processes and flows. Notes: Wide arrows: Liquid state; dashed arrows: Solid state; thin arrows: Gaseous state. On the final

arrows that do not have continuity in another unit operation: Final effluent, part is discharged in the river, part is conducted to a non-potable water reservoir, and part is sent to the Aquapolo Project; scum from settling tanks is conducted to digesters or disposed in landfill.

The motivation for the choice of this plant was based on the availability of data, its completeness, representativeness (in terms of scale, treatment flow, and treatment processes compared to other large-scale WWTPs of São Paulo megacity), and because this plant already applies one measure of resource recovery: Water reuse. It is noted that Cornejo et al. [36] also used similar criteria to choose WWTP in their study.

2.3. Data Collection for Application of The Framework in the Case Study

The input data to achieve steps 1, 3, and 4C of the framework (treatment configuration; qualitative and quantitative characterization of effluent and by-products; and identification of internal demand) were obtained with the managers and engineers of the plant (WWTP ABC). For this, a list of the necessary primary data (general data, characteristics of the treatment processes used, monitoring data, by-products, and environmental indicators) was prepared (Supplementary Material S1).

For characterization purposes (step 3), the substances considered for analysis were: Water, phosphorus, nitrogen, and organic matter. The water (treated effluent, reclaimed water, and water consumed by the WWTP) represents a relevant local resource for the context of the study area. Phosphorus (P) is a resource that is globally limited, and it presents actual scale recovery processes implemented in several countries where it is considered economically viable. In addition, P can be recovered from different units of wastewater treatment processes. Nitrogen is an important constituent (in quantitative terms) of municipal sewage, as well as P, and has potential as fertilizer. Organic matter is source for recovery of many products (e.g., energy from biogas and soil conditioner). Further information on research design is presented in the Supplementary Material S2 (2A).

The temporal boundary of the analysis comprised a period of one year (from 07/01/2016 to 06/30/2017). The definition of this period followed the recommendation of Brunner and Rechberger [37], and it was considered a reasonable period to determine reliable average values, since the period should be enough to counterbalance momentary instabilities of the analyzed system and seasonal variations. The analysis included all processes and unit operations of the WWTP ABC from the arrival of raw wastewater until the discharge of treated effluent (Figure 3).

The data to achieve the other steps of the framework were collected from various sources, consulting the related legislations on water reuse, sludge recycling (in the form of organic fertilizer and soil conditioner) and energy recovery, technical reports, regional databases, journal articles, and planning documents for the study area. For step 4, in order to complement the data (estimated volume and price of reclaimed water for non-potable uses in urban areas), we contacted the plant managers of WWTP that commercialize reclaimed water and the responsible secretaries of the city council of study area cities.

The comparison of recovery technologies options (step 9) considered evidence from the literature about the respective technologies. Scenario analysis was used to explore some possible resource recovery measures for the studied plant. Detailed information for each attribute/indicator can be found in the Supplementary Material S3.

2.4. Data Analysis

After data collection, both qualitative and quantitative data were organized into data spreadsheets for comparison purposes. Based on the collected raw data about the plant, mean concentrations, organic and nutrient loads, and removal efficiencies for the main parameters chemical oxygen demand (COD), biochemical oxygen demand (BOD), nitrogen (N) and P were calculated. In general, the results were represented as tables and graphs. The final step was the comparison between the recovery options according to the indicators. The outlook (recovery scenarios) was a result of the different assessment indicators given in this work (educated guesses) and based on the literature.

3. Results and Discussion

3.1. Application of the Proposed Framework for Resource Recovery in a WWTP in São Paulo Megacity

The results are organized and discussed according to each step of the proposed framework. Further information on each step is in Supplementary Material S2B–H.

3.1.1. Step 1—Existing Treatment Configuration

The first step of the framework included liquid and solid phases and the analysis of all the existing treatment units in the plant (Figure 3) as well as the expected upgrades for this facility. Detailed characteristics of all treatment units are summarized in Supplementary Material S2B.

Future upgrades of the studied plant are changes to increase its treatment capacity. The expected upgrades are to increase to 6 m^3/s, and a further stage to upgrade the settling tanks to increase the treatment capacity to 8.5 m^3/s. Currently, it is foreseen that there will be an increase of the treatment capacity to 4 m^3/s in 2023. It is important to take it into account when planning resource recovery strategies since the increase of the plant's capacity will imply increase of generated by-products (e.g., sludge) and will have effects on characterization (effluent and sludge quality).

3.1.2. Step 2—The Surrounding Areas of the WWTP

Understanding the local context is a crucial step to support future decisions about which resource(s) to recover. Firstly, we defined the area nearby the WWTP. The named group 1 includes the municipalities of the Great ABC Region (Santo Andre, São Bernardo do Campo, São Caetano do Sul, Diadema, Maua, Ribeirao Pires, and Rio Grande da Serra) and São Paulo city. Furthermore, a broader area (group 2) was considered, including four other municipalities of the metropolitan region of São Paulo (MRSP) (Biritiba-Mirim, Mogi das Cruzes, Salesópolis, and Suzano) due to their importance to agricultural activity (high values added to agriculture among the cities of the MRSP). Figure 2 shows the study area, comprising cities of groups 1 and 2. The main economic sectors correspond to those with the highest contribution to gross domestic product in the study region (groups 1 and 2). Figure 4 shows the distribution of the main economic activities in terms of the number of facilities in the study region.

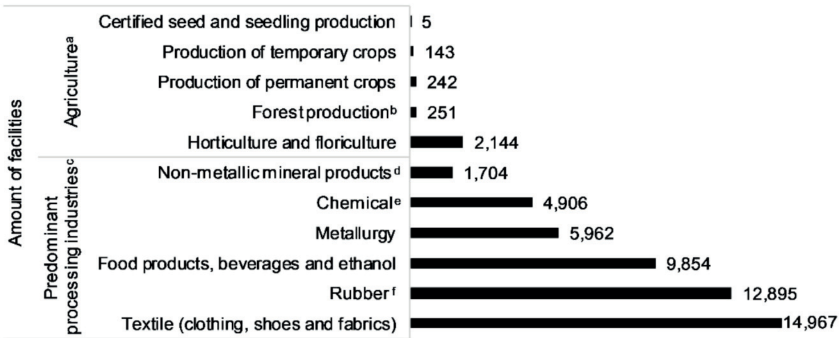

Figure 4. Predominance of agricultural and industrial activities in the surrounding area of the wastewater treatment plant. Notes: (a) Based on the Brazilian Institute of Geography and Statistics (IBGE) [38]; data refer to 2017; (b) it includes planted and native forests; (c) based on [39]; data refer to January to September of 2019; the automobile sector is not included. Other sectors were not included because they are not highlighted in the Great ABC region [40]. Other sectors correspond to the mechanical industry; electrical and communications industry; transport material industry; wood and furniture industry; paper, cardboard, editorial, and graphic industry; and footwear industry (23,390 facilities in total); (d) manufacturing of materials such as cement; (e) industries such as pharmaceutical, veterinary, perfumery, and others; (f) smoke, leather, fur, and similar industries.

In the group 1 region, there is a predominance of processing industries and other services (transport, post office; accommodation and food; information and communication; private education; health; among others) [41]. The main processing industries are automobile industries, chemical industries, metallurgy industries, rubber and plastic production, food industries, and textile [40].

Agriculture and livestock are not significant economic activities in the group region 1. Nevertheless, in the small city of Rio Grande da Serra, there is considerable agricultural activity (fruit and vegetable production and farms for chicken production) [42]. In quantitative terms, there are 5064 units considering agriculture, forestry, plant extractivism, and livestock in group 2 (considering the 12 municipalities) [39]. It is worth adding that in the rural zone of São Paulo city, there are about 428 units of agricultural production, particularly in the southern region, for fruit, ornamental, and leave crops [43].

In the analyzed region (group 2), the quantity of settlements is higher in horticulture and floriculture [38]. In addition, there are initiatives such as: Urban agriculture programs in Diadema and Santo Andre, community gardens in São Paulo city [44], and vertical farming. The products of horticulture in the region are diverse, but the crops linked to the highest number of farms are lettuce, cabbage, and coriander [45]. Therefore, this diagnostic (step 2) can support the identification of the local area needs and the potential demand for resources that could be recovered by the studied WWTP, which is discussed in step 4.

3.1.3. Step 3—Qualitative and Quantitative Characteristics of the Treated Effluent and by-Products

This step allows for the support of decisions on what recovery measures would be feasible for a specific facility. It is possible to identify resources that are present in which treatment stages and in what quantities. The analysis was based on the volumes of wastewater, consumption of inputs, and generation of waste in the period of one year. All treatment processes are summarized in Figure 3.

Regarding quantitative data, the average daily raw wastewater flow rate that entered the plant was 2.33 m^3/s. The total volume of the raw wastewater inflow rate during the analyzed period was 73,720,195 m^3 and the total volume of treated effluent was 71,266,865 m^3 per annum. Part of the treated effluent by the plant was discharged into the river nearby, another part was directed to the Aquapolo Project (423 L/s during the monitored period), and a third part went to an internal reclaimed water facility. This reclaimed water was used internally for washing of streets and installations, sealing of pumps, cooling equipment, and foam breaking.

The Aquapolo Project is the largest wastewater reuse facility in the southern hemisphere, and the fifth largest of its kind in the world. In the Aquapolo Project, the advanced treatment processes used are disk filters (400 microns), membrane bioreactor (0.05 microns), and reverse osmosis [46]. After this treatment, the reclaimed water is pumped to a Petrochemical Complex, mainly for cleaning of cooling towers and boilers [46]. The current capacity is to provide up to 650 L/s of water to the industrial complex [47].

Steps 3B and 3C (Figure 1) comprise the qualitative monitoring of the treated effluent and the by-products (Tables 3 and 4) to identify potential resources to be recovered. The removed grit and screening material are currently sent to landfills. The annually removed amount was about 765,755 kg of grit and 152,641 kg of screening material. The generation of screening material was 2.07 kg per 1000 m^3 of raw wastewater (plant influent) and 10.38 kg of grit per 1000 m^3. The generation of screening material was lower than the findings of a previous study [48]: Average of 6 kg per 1000 m^3, but in other WWTP in the São Paulo state. It is worth noting that the data on generated screening material and grit (of our studied plant) were underestimated due to maintenance of the equipment during part of the monitored period, which can explain the lower value.

Table 3. Quantitative data of by-products of the wastewater treatment plant (WWTP) and potential resources.

Unit	Material	Quantity [b]	Unit	Resources with Potential to be Recovered
Screening	Screening material [a]	554.55	kg/day	Energy
Grit chamber	Grit	3175	kg/day	Grit
Primary settling	Sludge	1093.8	m^3/day	Energy
	Scum	0.864	m^3/day	Energy
Secondary clarifier	Sludge	-	-	-
	Scum	9.09	m^3/day	Energy
Gravity thickeners Flotation thickeners	Thickened sludge	748.7	m^3/day	Nutrients
	Thickened sludge	250.36	m^3/day	Nutrients
Digesters	Digested sludge	1215.75	m^3/day	Nutrients
	Biogas	3036 [c]	Nm^3/day	Energy
Chemical conditioning and dewatering of sludge	Digested and dried sludge	112.9	ton/day	Fertilizer (P or biosolids) Energy

Notes: [a] It includes screening with fine, medium, and course screens; [b] data referring to the period between 1 July 2016 and 30 June 2017; for grit and screening material quantities there were missing data for some months due to maintenance; and [c] data from December 2017. Cells with "-": data not available or not measured by the wastewater treatment plant operators.

Table 4. Mean concentration of main parameters at different sampling points.

Parameter	Influent (Raw Wastewater) [a]	Final Effluent (Treated) [b]	Thickeners (by Gravity) Supernatant	Thickeners (by Flotation) Supernatant	Dewatering Centrate
COD (mg/L)	462.2	66.0	6970.0	118.3	1250.0
Dissolved COD (mg/L)	124.8	83.3	-	-	-
$BOD_{5,20}$	241.0	30.3	-	-	-
Total Phosphorus (mg/L)	14.8	3.9	23.9	3.8	6.1
Dissolved phosphorus (mg/L)	2.4	1.8	10.0	2.1	4.4
Total nitrogen (mg/L)	33.2	25.1	-	-	-

Notes: [a] Sampling point located at the entrance of the ABC WWTP (before grit chamber); [b] effluent of secondary clarifier. "-": data not available due to no measurement.

The total amount of produced dewatered sludge (or biosolids, which refer to stabilized sewage sludge) was 41,190 tons in the analyzed period (one year). The WWTP ABC had higher sludge production compared to a similar study [49], which obtained 2894 tons annually of biosolids produced in a WWTP in USA with a flow rate of 0.541 m^3/s using activated sludge process. However, it is emphasized that the amount of sludge produced depends on the treatment flow rate, the treatment processes used, and the composition of sewage.

In the anaerobic digestion of sewage sludge (of WWTP ABC), the mean biogas composition was 69.79% of CH4 (methane), 27% of CO_2 (carbon dioxide), 2.7% of N_2 (nitrogen), 0.59% of O_2 (oxygen), and <30 ppm of H_2S (hydrogen sulfide). The methane production was about 2118.8 Nm^3/day. Estimates regarding electric power generation from methane production are discussed in Section 3.1.7.

In the studied plant, the removal efficiencies were: 85.7% COD, 24.5% total N, and 73.5% total P. The COD load was 93,350 kg/day. The total P load that entered the plant during the analyzed period was 2997 kg/d, which totalized around 1094 tons/year. The total N load that entered the WWTP ABC was 6707 kg/day, or 2448 tons/year. Considering that 73.5% of the P total load was removed by the studied plant, which ended up in the sewage sludge, the content of P was estimated to be around 2.2 tons P per day in the sludge.

Analyzing the waste stream composition is essential to the selection of suitable resource recovery technologies. Different technologies may have strengths and weaknesses in targeting specific wastewater components [23]. Data for P concentration (Table 4) in secondary streams allow for technology options for recovery to be defined. The highest P concentration was observed in the supernatant from the gravity thickeners. There was no monitoring of P concentration in the supernatant of digesters. In the case where the nutrient concentration was below 20 mg/L, it was recommended to apply accumulation techniques such as: Wetland or microalgae cultivation, and physicochemical treatment [50]. There was no monitoring for nutrient content in sludge for the studied facility. However, a recent study [51] reported the mean value of 16.4 ± 2.1 (g P/kg of dewatered sludge) for the studied plant (ABC).

Characterization of influent and effluent quality of WWTP provided useful information for designing strategies and selecting processes for resource recovery [5,52]. The next steps aimed to guide on how the WWTP could be improved, defining strategies for recovering resources.

3.1.4. Step 4—Mapping the Demand for Recovered Resources

This step aimed to identify the needs for resources (water, nutrient, and energy) in the local context as well as potential customers (e.g., industries, farmers, and households) for recovered products. Consumption of water, electricity, and fertilizers in the surrounding area and internally in the plant is presented in Table 5.

Table 5. Estimated demand for the wastewater treatment plant and nearby locations for resources.

Demand	Sector	Water (m^3/month)	Electricity (kWh/month)	Fertilizer P_2O_5 (kg)
External	Processing industries	1,124,786 (food and beverage); 1,020,714 (chemical); 436,314 (textile); 367,722 (metallurgy); 247,293 (rubber); 206,790 (non-metallic mineral products); and 168,714 (automobile) [a]	50,450 [e]	-
	Agriculture	761,271 [b]	-	132,139 [g]; 93,961 [h]
	Urban purposes	5450 [c]	222 (households), 23,210 (public lighting), 2352 (stores/shops) [f]	-
Internal	WWTP analyzed	6622 [d]	2,598,708	-

Notes: [a] Based on [53], referring to 2015 and the study region (12 municipalities), considering only predominant industrial sectors; [b] data refer to 2015; based on [54] (data not available for four cities without predominant agricultural practices); [c] data from [55]; referring to November 2019; [d] potable water consumption (June 2016 to July 2017); [e] mean consumption per industry in São Caetano do Sul city; for all types of industries [56]; [f] mean consumption per unit in São Caetano do Sul city [56]; [g] total fertilizer sold per planted area in the study area (data not available for five cities, which do not have predominant agriculture activity); based on [57] referring to 2014; [h] total fertilizer used in the studied area (data not available for five cities as mentioned) based on [58], referring to 2015, planted area obtained from [59] and referring to 2016; "-" not applicable.

In Brazil, the highest water demand from industries is in São Paulo state (59.7 m^3/s). The industries of manufacturing of food products, beverages, cellulose and paper, petroleum products, biofuels, chemical products, and metallurgy correspond to 90% of the flow of the water consumption by the national industry [60]. The quality required for industrial uses is highly variable, depending on the sector and level of process sophistication. A further step could be to analyze the quality of the treated effluent to find out if it could meet the specific quality requirements of one industry or a group of them in the same sector. Then, it is possible to evaluate the need for additional treatment to water reuse.

In quantitative terms, in some sectors such as paper and cellulose, chemical products, textile, and cement industries, the water consumed for cooling (non-contact) can represent up to 94%, 95%, 57%, and 82% of the total water consumption, respectively [61,62]. It is worth noting that industries of chemical and textile sectors are predominant in the studied region and represent high water consumption rates (Figure 4 and Table 5).

Other important water use is agricultural irrigation. In Brazil, the south-eastern region corresponds to the largest irrigated area for agriculture; 34% of the total irrigated area [63]. Reclaimed water could be used for irrigation in agriculture, but currently there is not yet local regulation for water reuse for agricultural irrigation in the state of São Paulo.

The demand for non-potable urban purposes (irrigation of parks, squares, public cleaning, clearing of rainwater galleries, and sewage networks) was based on the volume reported by one plant as commercialized to urban purposes in São Paulo city (Table 5). Comparing the total water demand for the predominant industries, agriculture and urban use (4,339,054 m^3/month) (Table 5) and the treated effluent flow that is discharged into the river (4,341,600 m^3/month) by the studied plant, if directed to reuse, this flow would be sufficient to supply all the water demand for these corresponding purposes.

Electricity consumption data were collected for São Caetano do Sul city, which is close to the WWTP (Table 5) [56]. Regarding the internal demand of the plant, the average energy consumption of WWTP ABC was about 2.6 GWh/month (consumption for all processes). Considering the volume of treated sewage, the energy consumption corresponds to 0.42 kWh/m^3 of treated sewage.

In this paper, the local market value (of phosphate fertilizer, water, and electricity) was estimated to make the analysis more complete. The price for potable water is dependent on the consumed volume. Based on SABESP (service provider), the current fee for potable water in São Paulo city varies from 3.6 € per m^3 (for consumption higher than 50 m^3/month) to 9.3 € per month (for consumption lower than 10 m^3/month) in commercial, industrial, and public sectors [64]. This value varies among the cities. Regarding the reclaimed water, there is no standard price for the reclaimed water from treated effluent. According to information from one WWTP in São Paulo city, which sells reclaimed water, the price varies from 0.4 €/m^3 and 1 €/m^3, depending on the consumed volume and type of contract [55]. The price of phosphate fertilizers (monoammonium phosphate (MAP)) was estimated as 315 € per ton in 2017 [65] and superphosphate was 214 € per ton in 2019 [66].

Regarding other megacities, Table 2 provides an indication on which resources (water, energy, or P) are scarce in each megacity, supporting the identification on where resource recovery technologies could be more beneficial. Moreover, detailed sustainability assessments considering stresses based on local data are necessary to identify the most suitable technologies to each context [7].

3.1.5. Step 5—Relevant Legal and Regulatory Framework

In Brazil, legislation (regulation, quality standards, and requirements) related to wastewater treatment focuses more on standards for discharging the treated effluent than on standards for water reuse. In this section, current legislations related to water reuse, energy and nutrient recovery are addressed.

At a national level in Brazil, there are two national regulations for non-potable reuse: National Water Resources Council (CNRH) 54/2005 and CNRH 121/2010. The first defines general criteria for non-potable direct reuse, while the second establishes guidelines for non-potable direct reuse in agriculture and forestry. The states and municipalities may have more restrictive laws and regulations than the national ones [67].

In the state of São Paulo, where this study took place, the joint resolutions SES/SMA/SSRH n.1 (2017) and SES/SIMA n.1 (2020) govern the non-potable direct reuse of water for urban purposes, originated from WWTP, and establish guidelines and general criteria. There are quality standards for uses (e.g., landscape irrigation, washing of streets and other public and private spaces, and civil construction). Irrigation for agricultural uses, grazing and forestry is not included. The WWTP must have at least secondary treatment, disinfection, and filtration, and meet the quality standards and a microbiological characterization of the treated effluent [68,69].

In the state of São Paulo, there is also a decree (48138/2003), which determines some measures for the rational use of water, among which is the prohibition of use of potable water for cleaning streets, squares, and sidewalks, except in specific cases [70]. The Environmental Agency of the State of São Paulo (CETESB) has guidelines for irrigation in agriculture with treated effluent. The application is permitted for fruit gardens, raw uneaten crops, forage (except for direct grazing), reforestation areas, and forest plantations, and establishes some restrictions regarding areas of application and effluent monitoring (heavy metal concentration, thermotolerant coliforms, helminth eggs, sodium adsorption ratio, and electrical conductivity) [71,72]. At the city level, some legislations to promote water reuse from treated effluents for urban non-potable purposes are mentioned in Supplementary Material S2F.

The main barriers to water reuse projects are: No federal program or financial incentives for planning and implementation of water reuse projects (e.g., loan guarantees, tax-free); there are no nationally or locally defined goals (e.g., no obligations or incentives for industries to reuse); the criteria for urban reuse adopted (resolutions n.1/2017 and n.1/2020) in the state of São Paulo are perceived as very restrictive, do not consider agricultural irrigation, and hinder urban reuse [67]. Appropriate policies and the establishment of water quality regulations are required to encourage the creation of markets and the development of water reuse technologies [19].

Regarding energy recovery, the relevant legal and regulatory framework is discussed below. There is a regulation (SMA-079/2009) from the Environment Secretary of the State of São Paulo, which provides guidelines and conditions for operation of thermal treatment of solid waste for energy recovery (e.g., incineration of biosolids) [73]. The Brazilian Electricity Regulatory Agency (ANEEL) establishes the general conditions for the access of microgeneration and mini-generation to the electricity distribution systems (resolution 482/2012). In the case of self-producer, the electricity generated is to meet, partially or totally, the consumption needs of the producer, although the sale of eventual surplus energy may be authorized by ANEEL (law 9427/1996, [74–76]).

In Brazil, biomethane from wastes is an emerging biofuel, and the legal framework for biogas and biomethane recovery has been developed, especially for the state of São Paulo [77]. The regulations in the state of São Paulo about biomethane production are in Supplementary Material S2F. The state decrees n. 60,001 (2013) and 60,298 (2014) provide economic benefits (tax deductions) to utilities that recover biogas or biomethane [78,79].

The national regulation (CONAMA 498/2020) [80] defines the criteria and requirements for production and application of treated municipal sewage sludge (biosolids) in soil. Some requirements are environmental permission, treatment processes, criteria for application, and frequent monitoring of the biosolids quality depending on application. This regulation also defines conditions for cultivation of food crops consumed raw and crops whose edible part has contact with the soil as well as for pasture and forages, food crops that are not consumed raw, fruit trees, and non-food crops [80]. This regulation [80] has been recently published and has updated the previous regulation [81]. It expands opportunities for use of sewage sludge, and in general is more flexible than the previous regulation (in terms of frequency of analyses, guidelines for application, and permitted uses). Therefore, it is expected that this new practice of biosolids for agricultural use will be more widespread in the national territory, contributing to organic matter and nutrient recycling. Biosolids as a product to be applied in soil for agriculture must be registered in the Brazilian Ministry of Agriculture, Livestock and Food Supply (MAPA). It is also possible (based on standard n. 06/2016 of MAPA) [82] to register sewage sludge as a raw material, and to send it externally to a fertilizer or soil conditioner production process. More detailed information about standards on biosolids fertilizer and soil conditioner are in Supplementary Material S2F.

Besides legislation, regional planning documents were consulted (Master Plan of Great ABC region, Municipal Master Plans, Municipal Plan of Sanitation, and others) to identify whether they mention resource recovery from wastewater and/or set goals for implementation. The Policy on Climate Change of the State of São Paulo encourages the methane recovery from anaerobic digester of WWTP [83]. The Action Plan on Climate Change in the Great ABC mentions as strategic the biogas recovery from wastewater treatment plants to reduce GHG emissions. In addition, this plan states that sludge generated by the plants is disposed in landfills and has not explored its energy potential [84]. Municipal master plans (Mogi das Cruzes and São Caetano do Sul cities) mention, as one of their guidelines for the promotion and stimulation through tax incentives, the reuse from WWTP-treated effluent. The Municipal Plan of Sanitation of São Paulo states that new arrangements of reuse of sewage sludge for agriculture and civil construction as well as energy recovery from biogas are studied and highlight the potential of expansion of water reuse from treated effluent [85].

The analysis of the local institutional environment (addressed in step 5) allows for checking whether there is legal compliance and availability of supportive incentives [86]. Consequently, these results support the definition of resource recovery scenarios.

3.1.6. Step 6—Stakeholders Identification

The stakeholders (groups and institutions) are those interested in resource recovery measures, the potential beneficiaries, those who may be impacted by these measures, and the ones that have power to influence the process [29,87]. In our framework, stakeholders were divided into groups (Figure 1) based on their main roles. The stakeholders for assistance with recovery technology, research, and innovation include universities and research institutes as well as private companies in the region. We considered stakeholders mainly in the municipalities close to the plant: São Paulo city, São Caetano do Sul, Santo Andre, São Bernardo do Campo, and Diadema. Some stakeholders identified were universities that offer undergraduate and postgraduate courses in environmental science and engineering fields and conduct scientific research in related topics, research groups, and private companies on resource recovery technologies. Another group of stakeholders is the potential customers or end-users for the recovered product. It includes the main local farmer associations, trade and industrial associations of the study area, and others. All the mapped stakeholders are listed in Supplementary Material S2G.

The identification of stakeholders should also consider governmental agencies active in the field (e.g., water, energy, and agriculture sectors) that act as intermediary and have control on operation [88]. Thus, stakeholders regarded with political and legal support should be considered such as local governments, authorities, and environmental regulatory organizations. Some examples are water resources managers and the river basin committees, municipal secretaries of environment, and the Secretary of Agriculture. Additional stakeholders could be mapped such as the ones to provide funding or stakeholders supporting public awareness activities related to resource recovery acceptance (e.g., non-governmental organizations (NGO)).

During this process (step 6), potential roles and responsibilities should be assigned to different stakeholders and how they can engage and collaborate in the framework application towards resource recovery implementation. Some examples of key roles for universities and research institutes are to perform laboratorial analysis to ensure the quality of the product, to perform risk analyses, life-cycle assessments, and experimental studies, while NGO or public authorities could assist by awareness raising and promotion of resource recovery approach among the public. The company in charge of providing wastewater treatment services owns the studied plant and their plant managers or board of directors are important stakeholders. In our case study of the framework application, it was considered hypothetically that the water and sanitation provider would manage and coordinate the resource recovery system. We highlight that the list of stakeholders (Supplementary Material S2G) is not exhaustive and can be updated in the future.

All the identified relevant stakeholders could contribute with their opinions and participate actively in the resource recovery project formulation, which would result in an acceptable solution within the local context. Thus, design strategies could incorporate the stakeholders into the decision-making process for a better governance [22,89]. In step 6, it is expected that representatives of the mapped stakeholders' groups have regular meetings. It could include interactive workshops (group learning, discussion of the current state, and strategies and pathways, as proposed by Iwaniec et al. [90]). In these collaborative meetings, the stakeholders could provide practical recommendations for overcoming some of the barriers to planning and implementation of resource recovery target solutions [91].

Results from Laura et al. [22] corroborate with our findings regarding the lack of contact among the stakeholder's groups. For instance, WWTP managers and local authorities have very little collaboration with scientific experts and negligible relationships with NGOs, causing an absence of technical support to WWTP. Some measures to address this barrier are visits to universities for demonstration of technologies/studies related to resource recovery, pilot-scale projects in WTTP to increase the collaboration with research universities, benchmarking of successful operational practices in other contexts, and the regular stakeholders' meetings (as suggested previously).

3.1.7. Steps 7 to 9—Comparison between Resource Recovery Technologies Options

Previous steps of the framework assisted decision-making about which resource is worth being recovered. Based on this diagnosis (steps 1 to 6), the energy recovery and sludge management (e.g., nutrient recycling) seem to have higher potential and to be priorities according to consulted regional planning documents, and based on a previous study [31], when these options were reported as an area of interest by plant managers. The choice of recovery technologies considered the existing technology set-up in the plant, the level of development of the technology, and the availability of a thorough data basis for analysis. Only processes at full-scale (reported in the literature) were considered.

The scenario evaluation captured the necessary infrastructure updates, operational changes, and reuse applications [92]. Our purpose was not to produce an exhaustive evaluation of all possible technological alternatives that could be employed to recover resources. Instead, we focused on the most appropriated ones based on the previous steps of the framework and on previous literature.

The evaluated scenarios are listed as follows (Table 6):

- A: Struvite production from supernatant obtained from thickeners and digesters, and sludge dewatering centrate. Crystallization of struvite with magnesium (Mg) and pH increase via NaOH (sodium hydroxide). Examples: Fluidized bed reactor Pearl®, Struvia®, and others.
- B: Organic fertilizer and soil conditioner production from windrow co-composting of dewatered sludge. Pre-treatment by mixing different types of wastes (e.g., sawdust/wood chips, chopped urban pruning, sugarcane bagasse, and eucalyptus husk) to achieve the C/N ratio of 20:1 to 30:1 [93,94]. During composting, the temperature of sludge rises to about 50–60 °C, which reduces the pathogen content. After composting, screening using sieves.
- C: Energy recovery from biogas of anaerobic digesters. Co-digestion with food waste from street markets. Optimum temperature: 35–36 °C [95,96]. Otto cycle engine to generate electricity [97].
- D: Energy recovery by co-processing of sludge as raw material and fuel in kilns for cement industry. Pre-treatment for extra drying of sewage sludge (e.g., fluidized bed dryers and rotary dryers, solar drying, or by recovering residual heat from the cement kiln) until moisture content is less than 30%–25% [98–100]. The sewage sludge should be fed to a kiln system from the main burner, kiln inlet, or pre-calciner [99].

Table 6. Assessment of the recovery technology options against the indicators (step 9 of the framework). Further explanations are in Supplementary Material 3 (SM3). [102–152].

Indicator	Resource Recovery Technology Options			
Technical and Environmental	A. Phosphorus (Struvite Recovery)	B. Nutrients and Organic Matter (Sewage Sludge Co-composting)	C. Energy (Biogas from Co-digestion with Food Waste)	D. Energy (Co-processing of Sludge in Cement Industries)
Recovery potential	10%–40% from WWTP influent P and 85%–95% of P input of the recovery process [1] Estimate for the studied plant [2]: About 532.6 kg of P/day (in struvite)	Organic matter content in dewatered sewage sludge (50%–70%), N (3.4%–4%), P (0.5%–2.5%) and micronutrients [118–120]. Compost composition: organic carbon 224.5, P 16.7, TKN 28.1 (g/Kg) [121]. Estimate: 2.02 ton P/day in the dewatered sludge [11]	Co-digestion (an increase of 20% of organic loading rate) causes an increase of 21%–50% of methane yield compared to sewage sludge mono-digestion [95,130]. Current methane production: 2118.8 Nm^3/day; with co-digestion: 2565.9–3178.2 Nm^3/day. Estimated electric power: 8877.7–10,996.4 kWh/day [13]	Typical higher heating value (energy content) of dried sewage sludge is 11.10–22.10 MJ/Kg (mean value: 16.05) [141]. Estimate for the studied plant: 599,786.9MJ/day (thermal energy recovered) [11]
Technology maturity	Full-scale, but TRL 5 in Brazil [3] [15,107]	Full-scale, similar initiative already taking place in Brazil (TRL 9)[12]	Full-scale biogas recovery initiatives already take place in Brazil, including one plant with co-digestion in Paraná state (20,000 m^3 of biogas/day) (TRL 9) [131]	Full-scale, few applied in Brazil (sewage sludge corresponds to 0.4% of the total amount of co-processed wastes by cement companies in Brazil) [142] (TRL 9)
Resource utilization (e.g., energy and chemical consumption)	Electricity: 4.9–6.6 kWh/kg P rec., reactants consumption: $MgCl_2$*6H_2O 7.7–8.5 kg/kg P rec. and NaOH: 0.2–0.22 kg/kg P rec. [4] [103]	Low energy demand and low demand for reagents for composting (it may require micronutrient addition and additives to the product) [22]	Electricity consumption for pre-treatment: 35 kWh per ton of organic waste [132]. Electricity consumed by Otto cycle engine: 2% of the total generated (up to 219.9 kWh/day) [133]. Water consumption: 0.37 m^3 per ton of waste (in pre-treatment) [134]	Energy consumption for sewage sludge drying: 30 to 1400 kWh per ton of evaporated water (depends on the process) [143,144]. Estimate for the studied plant: 34,577.88 kWh/day [11]
Need for additional skilled labor	Require a high degree of operator skill to maximize the recovery efficiency, additional labor and maintenance requirements [108,109]	Additional personnel for operation of composting [22] (middle), simple operation[12]	Additional personnel for operation of biogas recovery system and of pre-treatment of food waste (middle, authors' estimation) [135,136]	Low (authors' assumption). No need of additional skilled personnel for sludge co-processing, especially in industries which already perform co-processing
Quality of effluent and sludge (removal of pollutants) and environmental concern	Low concentrations of phosphate and ammonia in the final effluent, P concentration in final effluent (around 0.4 mg/L) [5] [110], reduced energy demand (for returning side-streams flows and for aeration [101,103]), no need for reduction of heavy metals, and no organic micropollutants in the product, less production of surplus sludge [111,112]	Biosolids' land application avoids excess nutrients entering the environment because of their low nutrient contents compared with fossil fuel-based fertilizers [12], global warming impact is reduced [122], presence of heavy metals and persistent pollutants in the sludge and compost should be investigated [123], low gas emissions, possible generation of leachate [22,124]	Reduction of greenhouse gas emissions (52.4%–63.2% $kgCO_2$eq. per ton of waste and sludge) when comparing with digesting sewage sludge as single feedstock [134]. Considering a WWTP with a scale similar to the studied plant (2.29 m^3/s), biogas recovery would provide a reduction of 146.1 tons of CO_2eq./month [137]. The digestate could be used in agriculture	Release of contaminant gases [141]; no need of specific treatment for ashes [99]; significant reduction in sludge volume to be disposed of; replacement of fossil fuels; the ashes recovery causes a reduction of use of raw material [145]; reduction in greenhouse gas emissions; lower emissions of CO_2 and NOx [146,147]

Table 6. *Cont.*

Indicator	Resource Recovery Technology Options			
Technical and Environmental	**A. Phosphorus (Struvite Recovery)**	**B. Nutrients and Organic Matter (Sewage Sludge Co-composting)**	**C. Energy (Biogas from Co-digestion with Food Waste)**	**D. Energy (Co-processing of Sludge in Cement Industries)**
Economic				
Investment cost	4.4 to 10 EUR/kg P rec. [6] [102,103]	88,565 EUR [125]; 1.69 million EUR [94]; 150–310 EUR/ton DM (dry matter) [126]	750,000 EUR (for pre-treatment of food waste, considering 10 ton/day) [95]; 348,519–394,323 EUR (equipment total costs) [135,138]	11,704–45,016 EUR/(ton of sludge/day) [148]; sludge co-processing does not demand high investments [149]
Operation and maintenance cost	1.6 EUR/kg P rec. [7] [102]	22,546 EUR/year [125], 894–1254 EUR/month; 97,000 EUR/year [127]	50 EUR/ton of treated waste [95]; 0.003–0.005 EUR per kWh per year (repair and maintenance); 0.006 EUR per m^3 of biogas (biogas treatment); 2691 EUR/year (other maintenance costs) [135]	10–40 EUR/ton of dewatered sludge [150]; or 90–100 EUR/ton of dried sludge [127] (includes also investment costs).
Revenue from recovery	Price of struvite 0.3–1 EUR/kg P [101], profit from struvite production: EUR -0.04 to 0.46 per kg of struvite recovered each day [113], there are savings due to the avoidance of unwanted struvite encrustations in pipes and pumps [103]	Profit from compost sales, price of organic fertilizer: 14.5–17 EUR/ton [125,128]	Considering the electricity price (0.06 EUR/kWh) and the mean power generated by the WWTP, the avoided costs would be 185,641.6–229,944.2 EUR per year[14]. Avoidance of transport and disposal costs of organic waste to landfill (EUR 12.2/ton of waste per month) [139]	Reduces production, operational and maintenance costs of cement industries [93]; the saving out of using a 7.5% wet sludge in one kiln normally consuming 6.3 t/h of dry pet-coke (1% moisture) reach 8.0 EUR/h [151]; reduction of 66% of fossil fuel consumption [145]
Logistics (necessary changes)	Product is easy to transport [114], transportation until end-users necessary, installation of reactor for struvite production [8]	Requires transportation until end-users, space demand for composting and for storage of the compost, partnership with providers of other organic wastes necessary [8], it may require further sludge drying prior composting [93]	Requires storage, transportation, and pre-treatment of food waste (e.g., wheel loaders, crusher) [140]; biogas collection, transport, and storage system; biogas treatment (desulfurization); energy recovery unit; monitoring unit [135]	Pre-treatment of sludge drying necessary; transport of sewage sludge until cement industries; dosing and feeding system might be needed [99]; possibility of adaptations in the kiln exhaust system [152]
Societal				
Acceptance	4 (high) [9], struvite is not a well-known fertilizer among local farmers	3 (medium), may cause bad odour, more acceptable if the composting facility is located adjacent to the WWTP [116,129]	4 (high) (authors' assumption), interest in biogas recovery is reported in local planning documents	5 (high), considering cement industries perception on sewage sludge for co-processing [100]

Table 6. *Cont.*

	Resource Recovery Technology Options			
Institutional and political				
Accordance with policies and legal requirements	Possible, but national legislation (e.g., quality criteria of the product) needs to be developed to facilitate struvite recovery options [10]	Yes, there are sufficient regulations and policies [10]	Yes, there are sufficient regulations and policies, and incentives (tax deductions) to utilities that recover biogas [10]	Yes, there are national and state legislations that regulate co-processing in general [10]

Notes: P: Phosphorus; N: Nitrogen; TKN: Total Kjeldahl nitrogen; TRL: Technology readiness level; $MgCl_2*6H_2O$: Magnesium chloride; NaOH: Sodium chloride; CO_2: Carbon dioxide, NOx: Nitrogen oxides; EUR: Euros; [1]: Considering processes from liquid phase, based on [102,103]; [2]: Based on [104–106] and monitoring data from the plant; [3]: TRL in Brazil was estimated by the authors; [4]: Considering the process Ostara Pearl®; P rec.: Recovered phosphorus; [5]: P concentration in the final effluent was estimated by the authors; [6]: Considering processes Ostara®, DHV®, PRISA®, P-RoC®, and Nuresys®; [7]: Considers Nuresys® process; [8]: Authors' assumption based on site visit and observation; [9]: Estimated by authors based on [115–117]; [10]: Based on consulted legislations and regulations valid in the study region (authors' assumption); [11]: Explanation in SM3; [12]: Based on authors' experience; Biosolids: Compost; [13]: Explanation in the text (Section 3.1.7); [14]: Authors' estimation based on electricity price [135] and estimated generated power from co-digestion.

Technologies for P recovery based on sludge ashes were not included among the scenarios, because the plant does not perform sludge incineration and it is not a common route in Brazil (for municipal sewage sludge). The existing sludge disposal route in the plant is an important variable that influences the cost [101].

Existing P recovery techniques (e.g., struvite crystallization) are economically feasible with high P concentration streams (>50 mg-P/L), such as sludge liquors obtained from anaerobic digestion [153,154]. The recovery potential of struvite was estimated for the case study. Based on Jansen et al. [104], it was estimated that the thickeners' supernatant flow corresponded to 1%–2% of the raw wastewater flow, which approximately equaled to 35.1 L/s. The digester supernatant flow was around 29.23 L/s (0.5%–2% of raw wastewater flow), and the reject water from dewatering was 8.2 L/s. These side streams could be directed to a reactor for P recovery-precipitation, and about 10%–40% of P in the raw wastewater could be recovered [104]. There were no data for P concentration in the digester supernatant for our case study, but according to literature, sludge liquor (thickener supernatant, dewatering centrate, and the anaerobic digestion side streams) had total P concentrations between 110 and 289 mg/L [105,106]. Considering the flow of the P-enriched streams (72.53 L/s), a mean P concentration (100 mg/L), and the average rate of recovery of 85% from P influent (supernatant), the estimated P recovered would be 532.6 kg/day in the studied plant. This value would be enough to meet the annual fertilizer demand (P_2O_5) in the study area (Table 5).

However, for the removal of lower P concentrations, both operational and investment costs would be higher [102]. The studied WWTP does not have enhanced biological phosphorus removal (EBPR); thus, it could be a limitation for struvite recovery processes from the liquid phase [106]. The polyphosphate contained in P-accumulating organisms (PAOs) can be released as orthophosphate when EBPR sludge is digested [155], facilitating struvite recovery [156]. By combining EBPR and P precipitation, a great percentage of P in solution could be recovered as struvite [157]. If the studied plant applied EBPR, the P content in sludge would increase, consequently allowing for a higher recovery.

Regarding scenario B, a previous study [158] in another WWTP in Brazil showed that the composting process was enough to produce a compost that complied with the national quality standards (from the National Environmental Council) for heavy metals and pathogens. Thus, we expect that the composting scenario will be suitable to meet the quality requirements, but further regular analyses of the sewage sludge composition for the studied plant are necessary. A recent study by Nascimento et al. [51] investigated the quality of dewatered sludge generated in several plants in São Paulo state and assessed the suitability of the sludges for agricultural applications. Considering the results for São Paulo megacity plants, all sludge samples complied with the threshold values from CONAMA standards (National Environmental Council [81]), except for samples from two plants where Zn exceeded the maximum permitted. The authors considered the sludge promising as agricultural correctives to soils due to their high pH and micronutrient contents (Fe, Zn, and Mn). Regarding organic contaminants (e.g., pharmaceuticals and persistent organic pollutants) in sewage sludge, in Brazil, this research field is incipient so far. Souza et al. [123] evaluated aromatic polycyclic hydrocarbons (APH) in sewage sludge in Porto Alegre (Brazil) and found that the concentration was lower than the limits established by the European Union for APH. Another study [159] showed degradation of antibiotics during co-composting of sewage sludge with vegetable wastes (in Morocco).

Co-digestion with fruit and vegetable wastes was chosen for scenario C because it can improve biogas yield [160]. In addition, anaerobic sludge digesters are usually oversized due to low organic sludge loading, indicating capacity to receive other substrates, enabling co-digestion [97,161]. Considering methane production, the lower calorific value of methane (9.97 kWh.Nm-3CH4) [139], and assuming an electric conversion efficiency of 38% [135], the generator power capacity would be 405–501.7 kW. In addition, considering 8000 operating hours per annum by the motor-generator [135,162], the annual and daily power generation capacities were estimated (Supplementary Material S3 and Table 6).

A low temperature in digesters (22 °C) was noted for our case study. Thus, the following improvements in operation conditions were suggested: The increase of temperature of digesters, and frequent measurement of biogas flow and its composition. These matters (digesters operation) are currently under consideration by SABESP (wastewater treatment company). It is also possible to suggest the implementation of a co-generation system to recover thermal energy from exhaust gases of the engine for heating the digesters, which would increase the efficiency of the process [163].

For scenario D, the following aspects should be considered. The dewatered sludge in the studied plant contained humidity between 60.6% and 74.5%; thus, it would be necessary to dry the sludge before forwarding it to cement industries. Supplementary Material S2H contains some drying options. Another relevant aspect when exploring sewage sludge as fuel for co-processing is the proximity between the WWTP and cement industries. There are cement industries across the state of São Paulo, which makes it a possible alternative. However, in Brazil, fossil fuels represent 82% of calorific value in cement industries [142], and the use of sewage sludge for co-processing is irrelevant, being just some tests until the present moment. Sewage sludge corresponded to 0.4% of the total amount of co-processed wastes by cement companies in Brazil [142]. However, it is expected that it will increase significantly, particularly in south-eastern and southern regions in 2030 [164].

In developing countries, the most common routes for sludge disposal are landfilling and agricultural application [27]. These countries usually have little or no waste management infrastructure; therefore, properly controlled co-processing can be a practical, cost-effective, and more sustainable option instead of landfill and incineration [165]. In the metropolitan region of São Paulo, the sewage sludge is disposed in landfill [31]. In the studied plant, 113 tons of dewatered sludge was produced per day. Thus, scenarios B and D represent promising sustainable solutions to sewage sludge management.

Based on their quality, the fertilizer or soil conditioner products (scenarios A and B) could be used for several applications such as landscaping in agriculture to restore degraded land or to cultivate crops, especially sugarcane, eucalyptus, ornamental plants, and in some cases, coffee and vegetables, following the existing standards (step 5). The electricity produced by scenario C would be used to supply part of the internal demand in the WWTP (about 10%–13% of the total electricity consumed daily). For scenario D, the recovered energy would be used by cement industries. Considering two cement industries with kilns for clinker production (about 134 and 115 km of the WWTP ABC) [166], the thermal energy recovered by scenario D could meet about 2.3% of its total thermal energy demand annually (Supplementary Material S2H).

Social acceptance depends on the context and issues can be more critical for facilities in a densely populated region rather than in a nearly inhabited area [150]. One of the most influential factors associated with public acceptance in wastewater sector is the level of contact [167]. For scenarios C and D (energy recovery), the social acceptance is not truly relevant since these solutions do not directly affect the local population (no contact). Differently, the acceptance of plant managers and cement industries for these options could be aspects for further investigation.

In addition, concerns about environmental risks and human health associated with resource recovery measures can affect acceptance. For struvite recovery in agriculture, low acceptance can be attributed to low environmental awareness, lack of knowledge of public, and few scientific studies on this topic [168]. Until the present moment, struvite granules have been unknown by local fertilizers consumers in the São Paulo metropolitan region [18].

Regarding acceptance of compost from sewage sludge, there is a positive example in Jundiai city (60 km from São Paulo city) where the acceptance of the product is very good, and it does not represent a barrier. According to the technical director, responsible for composting facility, they have not done any prior acceptance studies, but they conducted initiatives such as promotion of visits to their plant, lectures, dissemination of information, sales offers, and participation in events with farmers. There was no resistance to the use of the product due to its origin (sewage sludge as raw material). The quality of the produced compost meets the standards (e.g., heavy metal concentration and pathogens-thermotolerant coliforms, Salmonella sp., and helminth eggs) [128]. In our scenario B, the composting plant could be built inside the WWTP area to reduce transportation costs, then only the compost volume (final product) would have to be transported.

As addressed in Table 6, all scenarios require further changes and demand necessary training for operators of the recovery processes. Further aspects that contribute to a better decision on recovery strategies are analysis of the final products and estimation of the market size [126]. However, concerning the economic indicators, cost calculations and estimates related to recovery processes are challenging, since there is no market for the recovered products in some cases. Indeed, the development of the market can occur in parallel to the implementation of resource recovery solutions in the WWTP.

The selected example WWTP already performs water reuse. Thus, in the future, other measures that could take place in parallel with the increase of its treatment capacity would be the expansion of water reuse for internal purposes, industrial supply and for other sectors such as irrigation, non-potable urban purposes, and for indirect potable reuse through discharging of the treated effluent in water reservoirs (of water supply systems).

The different scenarios (step 9) can provide new insights in the design of sustainable value chains. Delanka–Pedige et al. [169] have proposed the wastewater infrastructure attributes that support sustainability: Reuse-quality of water recovered from wastewater; safe pathogen reduction from wastewater; energy use and recovery in wastewater treatment; biofertilizer recovery from wastewater; and emission (direct and indirect) reduction in wastewater treatment. The recovery scenarios proposed (Table 6), together with the existing water reuse practice contribute to sustainability in all these attributes.

The proposed framework supports the application of a circular economy at a regional level, through the integration of production and consumption systems. In practice, the success of a circular economy approach in the water and sanitation sector will depend on some factors such as partnerships among stakeholders, user engagement, and overcoming of existing barriers [170]. In this context, there is a need for tools that enable the translation of scientific results to create an evidence base that supports decision-makers to act [171,172]. The proposed framework can be an example of tools that fit to this purpose.

Considering all indicators (Table 6 and Figure 5) for the studied plant, scenario B seems to be the most favorable for nutrient recovery due to low costs, high recovery potential, and a lesser requirement for skilled labor. For energy recovery, biogas recovery seems more favorable considering the set of indicators. In terms of institutional and political indicator, the biogas recovery scenario is the most favorable.

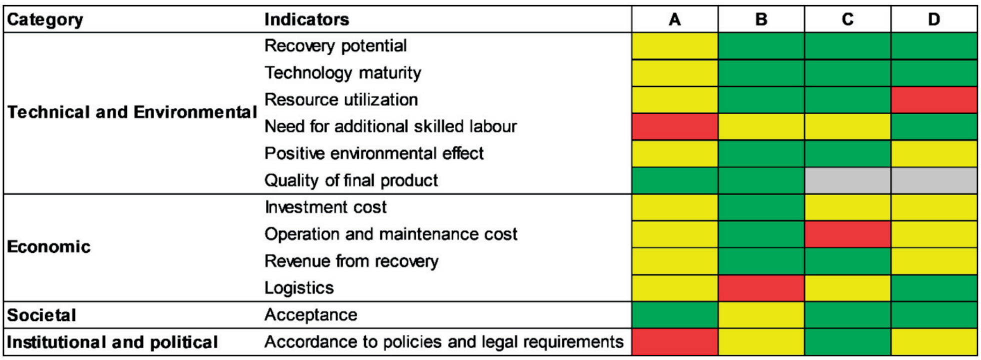

Figure 5. Comparison of resource recovery scenarios. (**A**) Struvite recovery; (**B**) co-composting of sewage sludge; (**C**) biogas recovery from co-digestion; (**D**) energy recovery from co-processing of

sewage sludge. Green corresponds to more favorable conditions, when the value of the attribute under evaluation is not problematic (it is considered positive); yellow represents intermediate situations; and red is used when the value of attribute raises a potential problem (it could represent a negative situation). Gray: Not applicable. More information on assessment and quantitative values are in SM4.

Steps 10 and 11 were not considered in this paper, since the resource recovery solution implementation was not part of this research, and decision-making depended on wastewater treatment plant managers' and local stakeholders' preferences. For instance, they could assign a high weight to one of the sets of indicators (e.g., economic or environmental), which would influence the final choice about the best solution among the defined scenarios [26]. Depending on stakeholders' and decision-makers' preferences, more than one scenario could be chosen, or they could be combined.

Overall, prior to a decision on implementation of any resource recovery technology (e.g., nutrient recovery), it is recommended that quantitative flows and qualitative data should be more thoroughly analyzed (e.g., nutrient content in the supernatants and in sludge, and other relevant parameters such as contaminants).

3.2. Strengths and Potential Improvements of the Framework

3.2.1. Strengths of the Proposed Framework and Comparison with Similar Studies

Some frameworks related to urban water management have been proposed and can play an important role to enable sustainability assessments, planning, and decision-making at different scales [173]. Frameworks can be useful to multiple purposes: To enable the diagnosis of a specific current situation, to be a management tool, to assess opportunities of improvement, and to facilitate stakeholder engagement and communication [173]. The framework tested in our study fits all these purposes.

Previous studies have developed frameworks for water reuse [21] and sludge management [22]. Papa et al. [21] developed a tool for evaluating the water reuse from technical and economic sustainability. Their framework aimed to judge the feasibility of wastewater reuse and considered the rating of the WWTP, hydraulic system (required for transportation), and the final user. The need for additional/polishing treatment of the effluent to satisfy quality criteria, and an increase of the costs (e.g., for plant upgrade, water distribution system, and the monitoring of reuse system) were considered as constraints to water reuse [21].

Laura et al. [22] created a framework to guide decision-making towards selecting sustainable options to handle sewage sludge. It included the evaluation of possible scenarios and considered four dimensions: Economic, environmental, social, and technical. Similarities with our study were the inclusion of stakeholder analysis (mapping), characterization data of sewage sludge, and analysis of local regulation.

O'Dwyer et al. [23] created a framework focusing on the optimization of design schemes of treatment plants and transport networks. In their assessment, environmental impacts and financial costs were considered for each scenario. Kehrein et al. [24] presented a framework for designing and planning of WWTP towards resource recovery activities. Some similarities compared to our framework are market analysis for recovered resources, inclusion of stakeholders, treatment performance analysis, and techno-economic and environmental assessment.

In our study, the proposed framework is not restricted to water reuse or sludge scenarios and serves for assessing other resource recovery measures, including more indicators and involving a variety of stakeholders. Thus, compared to previous developed frameworks, our framework is more comprehensive and offers descriptive instructions on how to approach each step. Another highlight is the final step of implementation and monitoring, which allows to optimize the recovery process and/or restart the framework application to combine with other resource recovery solutions.

One advantage of the proposed framework is that it could be easily presented to third parties with no specific technical background. Operationalization of the framework may be complicated and complex especially in data-scarce regions, but applying the framework in a collaborative way with key stakeholders (representatives of different groups/sectors) could facilitate the process and contribute to an increase in managers' and policy-makers' understanding of the subject (resource recovery).

Planning in the sanitation sector in developing countries should consider a multi-sectoral approach recognizing the interrelations between sanitation and other sectors such as water supply and solid waste management [174]. Van der Kooij et al. [17] highlighted the importance of making connections between wastewater treatment systems, agri-food systems, and ecological aspects to find more suitable recovery options. In our study, the application of the framework allowed us to identify these interactions and contributed to a better knowledge on recovery options.

Our framework aimed to capture context-specific characteristics to make a better decision. This addressed the future research needed mentioned by Diaz–Elsayed et al. [7] about the analysis of demand for resources and potential resources that can be recovered within design and local conditions. By applying our framework, it would be possible to identify potential challenges in the selection and implementation of resource recovery process configurations (e.g., water, energy, and nutrients), and as an additional step it was possible to restart the framework application (from step 7) to combine technologies to recover different resources. This should facilitate decision-making on integrated resource recovery since the previous steps were already concluded. Thus, the new framework had a practical value and allowed for plant managers to think about new potential solutions by providing relevant information. The proposed framework could also be complementary to the City Blueprint Framework, which is a tool that evaluates urban water management in a city [33].

3.2.2. Practical Challenges as well as Future Directions and Perspectives

After testing the framework with the case study, suggestions for improvements were evaluated. Step 7 (the choice of resource to be recovered) could be placed before step 6. Then, based on the target resource potential, key stakeholders could be mapped. This could make conducting step 6 easier and quicker; i.e., narrow down the number of stakeholders. Other suggestions for future applications of the framework were to limit the scale of analysis, for instance, to a smaller geographical area (at a city level or a neighborhood), or to a specific sector as an end-user (industry or agriculture). We believe that it could reduce the complexity of analysis and reduce the amount of data required, and, consequently, the challenges related to data collection and availability, despite losing the holistic perception of recovery alternatives and the view of the interactions at different scales.

Another possibility could be to start the framework application at step 6 (identifying stakeholders), particularly for contexts and places where data are scarce. It would likely facilitate (reduce time demand) the process to gather data needed for applying the other steps of the framework. For instance, if stakeholders from a local environmental agency/government were involved from the beginning, they could assist in the identification of the relevant legal and regulatory frameworks.

In this study, the authors considered the application of the framework for recovering of water, energy, and nutrients, although it is highlighted that the framework could be adapted for application even in different contexts (e.g., WWTP in urban or rural areas) and for other target resources.

The planning process requires detailed and accurate data and information. In step 9, in order to perform more accurate evaluations, it is recommended to replace qualitative limits by quantitative values as mentioned by a previous study [22]. This could be done in future studies, depending on data availability.

3.3. Limitations

The presented findings captured only a snapshot in time, conveying the current developments of recovery technologies and providing the framework application considering the data collected during a specific period. But the study region is very dynamic. Therefore, some aspects and data continually change in short or long terms (e.g., price of recovery technology, demand, and regulations), and the analysis through the proposed framework should be updated or restarted. According to Van der Hoek et al. [14], many external factors may change over time due to technological, environmental, economic, and market developments, and these uncertainties can influence the possibilities of resource recovery implementation. Other limitations noticed during application of the proposed framework was the lack of availability of some input data (e.g., some parameter concentration of treated effluent and sludge composition data, and costs for struvite precipitation in the Brazilian context).

Finally, we would like to emphasize that integrated evaluations at large-scale are characterized by a high degree of complexity (as mentioned by Papa et al. [21]). This was the case for our study, because we considered a large area, and the steps of the framework considered several types of data. The results of framework application depend on the overall availability of input data. Therefore, it highlights the need for improvement of monitoring practices either in a wastewater treatment plant or beyond (in other sectors; for example, water consumption in urban uses). There is uncertainty associated with secondary data used in the framework. For instance, although we considered the most updated available data, in some cases, they came from various sources.

4. Conclusions and Recommendations

Through the framework application, local context was deeply analyzed and the demand for water, energy, and P was identified. Some scenarios were recommended, and opportunities for improvement of existing processes were proposed.

Based on the results, all scenarios could be feasible for the studied WWTP, especially biogas recovery from co-digestion and sludge co-composting considering all the technical, environmental, societal, and political/institutional indicators. Local legislations seem to be favorable to implementation in all scenarios, except for struvite recovery, which needs further development. In addition, we recommend tests at pilot scale in the study region before applying struvite at full-scale WWTP. The suggested scenarios have potential to provide environmental benefits such as improvement of effluent quality (scenario A), low CO_2 emissions, reduction in global warming potential, and reduction of waste generation (scenarios B, C, and D).

With increasing demands for water, energy and food, particularly in urban areas, recovering resources from sewage is an important strategy. Considering only one WWTP in São Paulo megacity, the authors showed there is a potential to meet all the current demand for phosphorus fertilizer and non-potable water (main industries and agriculture) in the study region. Therefore, in quantitative terms, water reuse from the treated effluent could meet the current water demand for industrial and agricultural uses; and P recovery potentials from recovery scenarios could supply all the current demand for phosphate fertilizer in agriculture in the study region.

In summary, the strengths of the proposed framework are addressing the complexities of dynamic systems and integrating with relevant sectors and stakeholders, while the main limitations include the need of some data, which may not be available. The methodology used in this paper might be applied to other contexts, and the data from the case study (effluent and by-product characterization and potential demand) could be compared to other studies/regions. In addition, the comparison of recovery scenarios based on indicators and literature (Table 6) can be used as a basis for further studies under the circular economy perspective.

This paper provided a simple tool as a structuring mechanism to support resource recovery implementation from wastewater treatment, which is useful to managers and decision-makers. The results can help the elaboration of resource recovery projects. The framework refinement and use (presented here) can guide potential applications in other contexts.

In future studies, as soon as the market for recovered products develops, it is possible to calculate economic indicators using detailed local prices, and the social acceptance evaluation after consulting stakeholders and survey with the local community. Further studies could also explore stakeholder engagement and cooperation during framework application. Other relevant and necessary themes are the monitoring of sludge quality, removal of persistent organic pollutants in sewage sludge composting, analysis of risks to environment and human health from its application in soil, monitoring of P in reject water (thickeners, digester supernatants and dewatering centrate), development of local business models for resource recovery, multi-sectoral engagement approaches, and testing of the framework application in other cities.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/12/12/3466/s1, Supplementary Materials S1–4. Supplementary Material S1: List of data collected for the wastewater treatment plant; Supplementary Material S2 (2A–H): Further information concerning framework application; Supplementary Material S3: Further explanation regarding Table 6; Supplementary Material S4: Further explanation to Figure 5. References [175–210] are cited in the Supplementary Materials S2 to S4.

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water

MDPI

Supplementary Material

A Framework for Sustainable Planning and Decision-Making on Resource Recovery from Wastewater: Showcase for Sao Paulo Megacity

Mariana C. Chrispim [1,2], Fernanda de M. de Souza [2], Miklas Scholz [1,3,4,*] and Marcelo A. Nolasco [2]

Supplementary material 1: List of data requested by the wastewater treatment plant managers. It refers to the period between 01/07/2016 and 30/06/2017 for one treatment plant.

1. General data

-General information - historical data of the WWTP (e.g., year of the start of operation, possible changes or extension…).

-What is the percentage of different contributions from generators (sources) that make up the sewage received by the plant? (e.g. domestic, industrial, commercial, hospital)*.

-Flow chart of the treatment processes.

-Detailed description of the treatment steps - all the operational units (including the sludge line).

-Capacity- wastewater flow rate of the project (L/s).

-Current wastewater flow rate (L/s).

2. Monitoring data

-Raw wastewater flow rate that enters the WWTP (m^3/day).

-Hydrographs of flow rate (variation during the day and the year).

-Flow rate in each treatment unit*.

-Volume of treated wastewater (m^3/month).

-Raw data of concentrations of monitored parameters (COD filtered and not filtered, BOD, phosphorus, nitrogen series- NH_3, NO_3, VSS…) in the entrance of the WWTP and the exit of each treatment unit. Specify if the sample is punctual or compound (24h), day, and time of sample collection**.

-Location of sampling points.

-Mass balances existing for the studied period.

2.1. By-products

-Volume of course solid waste removed per day or monthly.

-Volume of grit removed daily or monthly.

-Volume of scum generated daily or monthly.

-Volume of sludge produced daily in each process of sludge treatment (e.g. primary settling tank) and its solid content.

2.2. Indicators

-Volume of chemical reactants used per month in each step of treatment (e.g. sludge conditioning and disinfection of effluent).

-Volume of produced biogas and data about its composition and volume produced per kg of COD removed**.

-Mean consumption of potable and non-potable water per month (e.g. reclaimed water for internal purposes in the WWTP or external purposes, and specify the purposes)**.

-Electricity consumption per month (points of energy consumption and points of energy generation)**.

- Volume of treated effluent that is directed to the Aquapolo project.

- Volume of treated sewage that is discharged into the river.

Note: The data marked with one asterisk was not provided by the company because there was no measurement of these parameters. The item marked with two asterisks was partially provided.

water

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Supplementary Material 2: Further information in the framework application

1. Text SM2 – 2A Methods (Step 3 of the framework)

Many techniques allow the assessment of environmental impacts of WWTP, such as LCA, Benchmarking, indicators, Carbon Footprint and Water Footprint, Material Flow Analysis, among others. Material Flow Analysis allows the assessment of a current status/situation and on a spatial/regional scale, and is considered an excellent instrument for public policy decision-making, as well as encouraging sustainable approaches, for example, planning and choosing strategies for resource recovery [175]. Material Flow Analysis approach is similar to the Step 3 of the proposed framework.

In this study, steps from 1 to 3 (of Material Flow Analysis-MFA) were done: the identification of the key (material flow related) issues; system analysis (selection of the relevant matter, processes, indicator substances (elements), and system boundaries); and quantification of mass flows and concentrations of indicator substances [37, 176]. The system analysed was the WWTP ABC.

Table A presents the main characteristics of the MFA for this study to meet step 3 of the framework. The table was based on the structure proposed by Krause and Rotter [177].

Table A- Characteristics of the Material Flow Analysis of WWTP ABC

Defining element	**Description of the system**
Problem description	(i) Wastewater contains resources that could be recovered during the treatment processes in the WWTP; (ii) increasing demand for water, energy and nutrients in the study area
Activities developed in the analyzed system	Municipal wastewater treatment; non-potable water reuse
Specific objective	(i) to characterize qualitatively and quantitatively the flows of materials in the treatment units of WWTP ABC; from this, (ii) to recommend operational and technological strategies of resources recovery that could be implemented.
Spatial boundary	Treatment processes of WWTP ABC
Temporal boundary	1 year
Indicators	Concentrations of COD (organic matter), N, P, wastewater flow rates in different locations during the treatment, and reclaimed water

2. Text 2B- Results: Step 1 (description of treatment units)

The following information is based on the WWTP project and considers the final stage/expected treatment capacity (8.5 m^3/s). The plant has two course screens with space of 80 mm between bars. Each screen has a usable width of 3 m and a thickness of 12 mm. The maximum flow rate per screen is 6.1 m^3/s. The screening material is removed and stored in containers (capacity of 3.5 m^3), and then is transported to be disposed of in landfills. The lift station is located downstream of the coarse screen and has the function of raise the sewage so that the sewage flow occurs by gravity in the following units of the liquid phase of the plant until the discharge of treated effluent. This plant has two medium screens (space of 25 mm). The maximum flow rate per screen is 6.1 m^3/s. The width of the channel is 2.6 m and the thickness of bars is 15 mm.

Another stage in the preliminary treatment is the grit chamber. In this plant, there are aerated grit chambers and a clamshell removes the deposited grit. About 85-90% of grit material with diameter equal or higher than 0.2 mm is captured. The plant has three grit chambers with total volume of 3,282 m^3. The air flow rate (m^3/min.m) is minimum: 0.13 and maximum: 0.45.

The next step is the primary settling tank. The plant has eight primary settling tanks, which is equivalent to a total volume of 37,800 m^3. The hydraulic retention time with the mean daily flow rate is 1.14 minutes, and 0.86 minutes with the maximum hourly flow rate. There are mechanized sludge scrapers that direct the sludge to concentration wells, from where the sludge is pumped to the thickeners by gravity.

The biological treatment occurs by conventional activated sludge process. There are eight aeration tanks, which are fed with effluents from primary settling tanks plus recirculated activated sludge from secondary clarifiers. The dimensions of the aeration tanks are: 25.5 m wide, 115 m long, average water height of 6 m, and unit volume: 17,595 m^3. Considering all tanks, the volume is 140,760 m^3. Detention time is 4.32 days.

There are 14 secondary clarifiers in the plant, with a total volume of 93,016 m^3. The retention time is 2.86 hours with the mean wastewater flow rate and 2.12 hours with the maximum flow rate. The maximum flow rate of recirculation is 32,555 m^3/h.

The solid phase treatment consists in four thickeners by gravity with mechanical removal (by pumps) of the thickened sludge and the exit of the liquid supernatant is by gravity. Also, there is a fine screen (space of 6 mm) located upstream of gravity thickeners. There are six flotation thickeners with dissolved air, and the exit of its liquid supernatant is by gravity. Then, the stabilization of sewage sludge is by anaerobic digestion (in two stages). The plant has eight digesters with hydraulic retention time of 22 days. There is a chemical conditioning of the digested sludge (with dosing of $FeCl_3$ and CaO) for further dewatering by press filters. There are 150 filters with capacity of 15 m^3 and operates 16h per day.

All the units of each stage of treatment did not operate all the time. During the evaluated period there were one course screen and one medium screen, two grit chambers, four primary settling tanks, four aeration tanks and five secondary clarifiers operating.

In this plant there is a Non-Potable Water Reuse Unity. In this unity, the effluent passes through a basket filter system (spacing of 0.6 mm) and hypochlorite dosage. It should be noted that in the analysed period, due to operational problems, there was no addition of hypochlorite.

3. Text 2C - Step 2

In Biritiba Mirim the agriculture is the main economic activity, and in Salesópolis agriculture is the third more important economic activity [41]. There are 71,873 processing industries in the ABC region and Sao Paulo city [39].

Regarding all analysed municipalities of the broader area (Group 2), the predominant economy activity is services [41].

From the perspective of installed production competence, the economic sectors that are considered strategic in the municipalities of ABC region in the industrial sector are: manufacturing of parts and accessories for vehicles; manufacturing of vehicles, buses and pickup trucks; manufacturing of plastic and rubber products; metallurgy and production of metals; chemicals production, and in services sector: information technology; and transport and logistics [40].

Some examples of industrial complexes in this region are Brazilian Complex of Cosmetics, Capuava Petrochemical Complex, Sertaozinho Complex of industries, and Technological Complex of Pottery [42]. Group 1 concentrates many vehicle companies: Volkswagen, Ford, Mercedes-Benz, General Motors and Scania [183].

There are urban Agriculture Programs in Diadema and Santo Andre [186], with 26 community gardens in Diadema [187], about 40 community gardens in Sao Paulo city (East zone) [44] and an urban farm located in Mercedez-Benz factory.

4. Text 2D- Step 3

The processes of Aquapolo Project for industrial reuse are advanced treatment with disc filters (400 microns), anoxic reactor, aerobic reactor, membrane bioreactor (with 0.05-micron pores) and reverse osmosis [191].

Regarding Table 3, there were missing data on grit and screening material generation for four months and three months, respectively, during the first year monitoring period due to maintenance of these units (the facility did not measure the generation during these months.

5. Text 2E- Step 4

Most common water applications in industries are: sanitary (restroom, kitchen and others with direct human contact), raw material (water incorporated in the final product or the water used to obtain an intermediate product, auxiliary fluid (for cleaning or chemicals reactants and solutions preparation), electricity generation, fluid for heating or cooling and others (e.g. irrigation of green areas) [62].

The urban demand for non-potable urban purposes (irrigation of parks, squares, public cleaning, clearing of rainwater galleries and sewage networks) is difficult to estimate (due to lack of monitoring/available data) and it is variable.

6. Text 2F- Step 5

-It is worth highlighting the sludge management is complex and surpass the boundary of WWTP.

-Other water reuse regulation is CNRH 153/2013, which establishes guidelines for aquifers recharge.

-Examples of vehicles wash covered by the resolution n.1 (2017): cars, trains, bus, airplanes and trucks for waste collection [68].

-The State Water Council established CRH 204 (in 2017) to complement the resolution (n.1/2017) [67].

-Complement regarding Decree 48138- except the cases where the existence of material that is harmful to health is confirmed.

-At the city level, Sao Paulo has the legislation 16174/2015 which establishes rules and measures to promote water reuse for urban non-potable purposes from treated effluents and rainwater harvesting [189]. Other example of municipal legislation is of Sao Caetano do Sul city (5329/2015) which mentions the incentive to use reclaimed water for purposes that tolerate lower quality water, in industry, commerce and general services, not including human consumption and food preparation, among other activities which require potable water [188].

-There is a regulation that determines the quality of biomethane from landfills and wastewater treatment plants (ANP -Brazilian National Agency of Petroleum, Natural Gas and Biofuels, 685/2017) [184]. In the State of Sao Paulo, ARSESP (Regulatory Agency of Sanitation and Energy of the State of Sao Paulo) regulates (deliberation n. 744/2017) the conditions for distribution of biomethane from agrosilvopastoral waste, solid urban waste and sewage treatment plants. The regulation REN 687/15 (ANEEL) [178] complements the regulation 482/2012.

-The State of Sao Paulo set as a goal to increase, until 2020, the participation of 55% to 69% of renewable energies in the final consumption of energy of the State (including biogas) [190].

-Sewage sludge legislation includes requirements such as environmental permission of the facility which produces the fertilizer based on sewage sludge. In comparison to previous regulations, this regulation is more flexible; for example, it does not require analyses of some parameters such as viruses [80].

-The standard n. 25 (MAPA, [180]) considers sewage sludge as an organic fertilizer and classifies it in group D specifying the conditions of its composition and label (with nutrients content and restrictions of application). According to this standard, the use of this type of fertilizer is forbidden for pastures and cultivation of vegetables, tubers and roots, and flooded crops, as well as other crops whose edible part encounters the soil. The standards n.27 and n. 07 (MAPA) [179, 181] establish the maximum limits for contaminants (e.g. pathogens and heavy metals) in organic fertilizer and for soil conditioner.

-The forecast of Municipal Plan of Sanitation of Sao Paulo includes incentive programmes for water reuse produced by the WWTP for urban reuse, civil construction applications, and irrigation of certain crops, practices to accelerate the reuse of biosolids, and to implement systems of biogas recovery [85]. Biosolids are defined as the sludge treated at a level (e.g. anaerobic digestion, alkaline stabilization and others) that allows its application for different further uses or safe disposal [192].

7. Text 2G- Step 6

-Stakeholders identified in Group B: Federal University of ABC (UFABC), Universidade Metodista de Sao Paulo, Unifesp (campus Diadema) and University of Sao Paulo. These institutions were identified based on CERTI [40]. Main research groups related to the field were identified: International Reference Centre on Water Reuse (CIRRA-USP), Research Group in Water, Sanitation and Sustainability (USP), Technologies in Environmental Sanitation group (UFABC), Bioenergy research group (USP), Renewable Energy group (UFABC) and INOVAUFABC (innovation agency). Some companies were identified as recovery technologies suppliers (sewage sludge treatment): Arcori Process solutions, Estre; Oxien (energy and phosphorus recovery); Algae Biotecnologia (microalgae solutions).

-Stakeholders group C: main local farmers associations Collectives Cooperapas (Agroecological Cooperative of Rural farmers of Água Limpa and South Zone of Sao Paulo), APROATE (Association of organic farmers of Alto Tietê) and Municipal Agriculture Houses, the private company BeeGreen responsible for a vertical farm in São Bernardo city, Trade and Industrial Associations of ABC region cities, ABISOLO (Brazilian Association of Industries of Technology in Vegetable Nutrition).

-Stakeholders group D: water resources secretaries and the River basin Committee of Alto Tietê -subcomitee Billings Tamanduateí, Municipal secretaries of environment, Federal Superintendence of Agriculture, Livestock and Food Supply of São Paulo, Secretary of Agriculture and Supply of the State of Sao Paulo, the environmental regulatory agency CETESB office in Sao Paulo city (Santo Amaro), Municipal Council for Sustainable and Solidary Rural Development. Additional stakeholders could be mapped such as the ones for funding (Brazilian Development Bank-BNDES, The Brazilian Innovation Agency- FINEP, donor agencies, foundations, impact investors or private funding), and stakeholders for supporting through public awareness activities related to resource recovery acceptance (NGOs) (e.g. Institute GEA- Ethics and Environment, and Global Sustainable Development Association of São Bernardo do Campo).

8. Text 2H-Steps 7 to 9

-In scenario D, main processes for pre-treatment for extra drying of biosolids (dewatered sewage sludge) are belt dryers, fluidized bed dryers and rotary dryers, disc, paddle and thin film dryers; solar drying; or by recovering residual heat from the cement kiln for drying the biosolids [98-100].

-The estimate on thermal energy recovered by Scenario D in relation to the total energy demand considered the data from 2013 (most recent data) regarding thermal energy consumed by the cement industries (GJ per ton of cement), and the capacity of cement production per year in the cement industry with kiln for clinker production (megatonnes per year), in industries which are closer to the WWTP (in Salto de Pirapora and Votorantim cities) (data from Cetesb [166]). Considering these two cement industries with kiln for clinker production, the thermal energy recovered by Scenario D could meet 2.3% of the total thermal energy demand annually.

-Besides economic benefits, resource recovery can generate societal value/benefits. For small producers (farmers), nutrient recovery can improve their life quality, reduce their expenses with fertilizer, and increase their production [26].

-One limitation of the study was to estimate the costs of recovery technologies due to no real application/implementation in the area.

-Depending on the composition of struvite, other fertilizers rich in N and K may be needed to meet the nutrient requirements based on the demand by the market in the region.

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water

Supplementary Material

A Framework for Sustainable Planning and Decision-Making on Resource Recovery from Wastewater: Showcase for Sao Paulo Megacity

Mariana C. Chrispim [1,2], Fernanda de M. de Souza [2], Miklas Scholz [1,3,4,*] and Marcelo A. Nolasco [2]

Supplementary material 3: Further explanation for Table 6.

1. General notes

The units of values are expressed in the Table 6 and depend on type of data, quantitative or qualitative. For simplification reasons, the technical and environmental indicators were grouped in one category, but these could be separated depending on the user's preference. For economic indicators, the costs found in literature were converted to Euro (considering 1 Brazilian real equal to 0.17 euros). For institutional and political indicator, it was analysed the existence of current legislation or if it needs to be changed for each scenario implementation. The logistics parameter was assessed considering the logistics challenges definition mentioned by Cordell [29]. The acceptance scale was created inspired by Laura et al. [22] and it varied from no accepted (1) to highly accepted (5).

2. Scenario A (Struvite recovery)

2.1. Technical and Environmental indicators

-Recovery potential rate: considering the processes such as Ostara pearl®, Crystallactor® and ANPHOS® based on Desmidt et al. [102]; Egle et al. [103]. Estimate of phosphorus recovery by struvite production for the studied plant was based on data from Jansen et al. [104], Münch and Barr [105], Zhou et al. [106] and monitoring data from the plant, as explained in section 3.1.7.

-Technology maturity: based on data about status/scale of P recovery technologies from Chrispim et al. [15] and Xavier et al. [107].

-Resource utilization (energy and chemical consumption): Based on Egle et al. [103], considering the process Ostara Pearl®.

-Need for additional skilled labour: data from Stratful et al. [108]; Sikosana et al. [109].

-Quality of effluent and sludge (removal of pollutants and environmental concern): precipitation of struvite can remove 80-90% of soluble phosphate and 20-30% of soluble ammonia [110]. P concentration in final effluent was estimated based on the raw influent data; reduced NH_4 back-flow results in a lower energy demand for aeration [103]; no need of reduction of heavy metals and no organic micropollutants in the product [111].

2.2. Economic indicators

-Investment costs: rec = recovered. Data based on Egle et al. [103] and Desmidt et al. [102] considering processes Ostara®, DHV®, PRISA®, P-RoC®, and Nuresys® treating 60 $m^3.hr^{-1}$ wastewater containing 120 $mg.L^{-1}$ PO_4-P. Egle et al. [103] calculated the annual costs (including investment + operational costs).

-Operation and maintenance costs: The data considers Nuresys® process treating 60 $m^3.hr^{-1}$ wastewater containing 120 $mg.L^{-1}$ PO_4-P [102]. The processes from side-streams are economically feasible [192], it should include the cost of magnesium (reactants).

-Revenue from recovery: market price of struvite [101], profit from struvite production [113]; savings due to the avoidance of unwanted struvite encrustations [103].

-Logistics (necessary changes): easy transportation from Ahmed et al. [114]. Other cited necessary changes were author's assumption based on site visit and observation.

2.3. Societal indicator

-Acceptance: Estimated by authors based on Oyama [115] and Bena-Filho [116], considering struvite fertilizer from human urine, acceptance value estimated in 4: more acceptable than composted sewage sludge [117].

2.4. Institutional and political indicator

-Accordance to policies and legal requirements: based on consulted legislations and regulations valid in the study region (authors' assumption).

3. Scenario B (Sewage sludge co-composting for organic matter and nutrient recovery)

3.1. Technical and Environmental indicators

-Recovery potential rate: Nutrient content in sewage sludge from Fytili and Zabaniotou [118]; Tyagi and Lo [119]; Samolada and Zabaniotou [120]. Data about compost produced from SABESP considering a WWTP with sewage sludge composting in Franca (Sao Paulo State, Brazil) [121]. The estimate value is an average and was calculated based on P removal efficiency of the WWTP ABC, P concentration in the dewatered sludge from Nascimento et al. [51] for the same plant (16.4 g/kg), and the produced amount of dewatered sludge per day (112.9 ton) of this plant.

-Technology maturity: Based on authors experience. There are many full-scale composting processes reported in the literature, few of them in Brazil.

-Resource utilization (energy and chemical consumption): No associated energy consumption and 10-50% additional requirement of reagents needed for composting [22].

-Need for additional skilled labour: Based on data from Laura et al. [22] in Guatemala, 10-20% additional personnel for operation of composting. Based on authors estimation, medium level of need of skilled labour. Simple operation mentioned by Leite [201].

-Quality of effluent and sludge (removal of pollutants) and environmental concern: mitigation of excess nutrients entering the environment in comparison with fossil fuel based fertilizers [12], as the sludge is used as replacements of fertilizers, significant reduction of global warming impact (from 32.4 to -18.8 kg CO_2 eq) [122]. Concern about pollutants in the sludge [123]; low production of gas emissions [22]; leachate generation [124].

3.2. Economic indicators

-Investment costs: capital cost from Visentin [125] in Botucatu, Brazil; data cost from Tarpani and Azapagic [94], considering an aerated composting facility in UK. The third data corresponds to total cost based on Kacprzak et al. [126] in relation to the amount of dry matter and considering European countries. Leite [201] states that investment costs of windrow composting are low.

-Operation and maintenance costs: from Visentin [125] based on a study in Botucatu, Brazil; standard operating costs from Wei et al. [127]; annual operating costs from Wei et al. [127], considering data for a windrow composting and moisture content of 70%, this cost includes cost for maintenance and operation, labour, bulking agents, energy and contingency.

-Revenue from recovery: price of organic fertilizer refers to December 2017 from a WWTP that produces organic fertilizer by composting in Jundiaí city, Brazil [125].

-Logistics (necessary changes): moisture values above 65% interfere with the process, calling for sludge dewatering (>35% dry solids) prior to composting [93].

3.3. Societal indicator

-Acceptance: acceptance based on Bena-Filho [116]; bad odours concern [129].

3.4. Institutional and political indicator

-Accordance to policies and legal requirements: based on the information gathered in Step 5 about related legislations.

4. Scenario C biogas (Co-digestion of sewage sludge and organic food waste)

4.1. Technical and Environmental indicatorsVolume of treated wastewater (m³/month).

-Recovery potential rate: VS = volatile solids. The increase on methane production was calculated based on data from La Cour Jansen et al. [130] and Bolzonella et al. [95]. La Cour Jansen et al. [130] evaluated co-digestion of sewage sludge with food waste. Their main result was that an increase of 17% of OLR (Organic Loading Rate, in Kg.VS/m³.day) caused an increase of 21.2% of methane yield. Bolzonella et al. [95] concluded that an increase of 20% in OLR resulted in an increase of 50% of biogas yield. The estimates of current methane production and production with co-digestion, and electric power considered the following data. The methane production is around 2118.8 Nm³/day. With co-digestion this value could be increased to 2565.9 Nm³/day (increase of 21%) or 3178.2 (increase of 50%, assuming 69.79% of methane in biogas). Considering it, the lower calorific value of methane (9.97 kWh.Nm-3CH4) [139] and assuming an electric conversion efficiency of 38% [135] the electrical power would be 405.05 – 501.71 kW. In addition, assuming 30 days off per year for system repair and maintenance, the working hours of the biogas plant was considered as 8,000 h/year [135, 162], the electric power would be around 3,240,385.0 – 4,013,689.1 kWh/year or 8,877.7 – 10,996.4 kWh/day.

-Technology maturity: Energy recovery from biogas to supply internal demand is an option very spread over the world [208]. There are some examples in Brazil, WWTP Arrudas, in Belo Horizonte and WWTP in Ribeirão Preto city [135] most of them are biogas recovery from mono-digestion. There is an experience of co-digestion at one WWTP in Paraná State (full scale) [131] and some studies at experimental scale [202, 205]. Authors estimated TRL as 9 for Brazilian situation.

-Resource utilization (energy and chemical consumption): Data about electricity consumption in pre-treatment are from Edelmann et al. [132], considering a WWTP in Switzerland, the pre-treatment with mixporter, macerator, pumps, pasteurization, stirring of the storage tank and stirring and pumping while digesting. Data of electricity by Otto cycle engine are based on Döhler et al. [133]. Water consumption data from Edwards et al. [134].

-Need for additional skilled labour: Based on data from Brazil [135] and Wiese [136]. Based on authors estimation, medium level of need of skilled labour.

-Quality of effluent and sludge (removal of pollutants) and environmental concern: data of reduction of greenhouse gases emission calculated based on Edwards et al. [134], considering co-digestion of sewage sludge (with 16.5 and 20% of food waste) in Australia. This reduction is compared to the reference scenario (destination of food waste to landfill with energy use, and anaerobic digestion of sludge, followed by energy recovery and destination of biosolid to agriculture). Data of emissions of a similar plant are from Forbes et al. [137].

4.2. Economic indicators

-Investment costs: cost of pre-treatment is from Bolzonella et al. [95], including waste crushing, removing ferrous materials, mixing and removal of floating part and bottom. Cost of equipment are from Brazil [135] and Felca et al. [138] and refers to a WWTP with population equivalent of 100,000-130,000 inhabitants. The equipment considered were: Otto cycle engine with 176 kW power, biogas treatment system (bio-desulfurizer and refrigerator with activated filter - to remove H_2S, moisture and siloxanes), gas compressor, 400 m³ gasometer, biogas transport system (conductor tubes, valves blocking, condensate removers and pressure gauges), electrical installations for the generator engine, biogas flow measurement, biogas composition measurement, flaring system (in case of excess biogas production). The cited studies [135, 138] did not consider co-digestion.

-Operation and maintenance costs: 50 EUR for pre-treatment of organic fraction of municipal solid waste is from Bolzonella et al. [95]; repair and maintenance costs and biogas treatment maintenance costs are from Brazil [135]. The repair and maintenance costs included the control of the starting sequence, tightness control, oil and coolant change, back pressure measurement and exhaust gas quality, verification and replacement of spark plugs, replacement of spare parts and others. The maintenance cost of the biogas treatment system included: replacement of activated carbon, preventive maintenance of the bio-sulfurization and the refrigerator [135]. Other maintenance costs are from Brazil [135] and include maintenance of electric installations, and maintenance of equipment.

-Revenue from recovery: price of electricity based on Brazil [135], considering the electricity produced by co-digestion (4,013,689.1 kWh/year). Avoidance of transport and disposal costs of organic waste to landfill, considering 705 ton of organic waste per month [139].

-Logistics (necessary changes): need of storage, pre-treatment and transport of food waste reported by Krupp et al. [140]. Biogas collection, transport and treatment system, energy recovery unit and monitoring [135].

4.3. Societal indicator

-Acceptance: Not found. Authors assumption. There is an interest in biogas recovery as reported in local planning documents. In addition, acceptance is not considered relevant for this scenario since it does not affect directly the local population.

4.4. Institutional and political indicator

-Accordance to policies and legal requirements: based on the information gathered in Step 5 about related legislations.

5. Scenario D (Co-processing of sewage sludge in cement industries)

5.1. Technical and Environmental indicators

-Recovery potential rate: Heating value of dewatered sludge (dry basis) considered the data from Syed-Hassan et al. [141], which is an average based on 32 values reported in 18 literatures, and other references also have reported values in this range [199]. The WWTP ABC generates 112.9 tonnes/day, with a mean moisture 66.9% (37.37 tonnes/day of dry solids of sludge). Considering the calorific power 16.05 MJ/Kg of dry solids - from Syed-Hassan et al. [141], it results in 599,786.90 MJ/day. Considering 1 kWh=3,6 MJ, the recovered energy would be 166,607.47 kWh/day.

-Technology maturity: TRL 9. There are many full-scale co-processing experiences with sewage sludge in cement industry in China, Japan, USA [99, 148, and 196]. Data for Brazilian situation in cement industries refer to 2017 and is from ABCP [142] -fossil fuels represent 82% of calorific value in cement industries; sewage sludge corresponds to 0.4% of the total amount of co-processed wastes by cement companies. In Brazil, about 70% of the installed capacity of cement industries with kilns for clinker production are licensed for co-processing (referring to 2017) [142].

-Resource utilization (energy and chemical consumption): Drying processes have the following requirements of energy consumption: convective dryer varies from 700 kWh to 1400 kWh per ton of evaporated water, conductive dryer (disc, paddle and thin film) 800 kWh to 955 kWh, and solar drying between 30 kWh and 200 kWh [143,144].

-Need for additional skilled labour: Not found. But based on authors assumption there is no need of additional skilled personnel for sludge co-processing, especially in industries which already perform co-processing (with other wastes). The consulted literature did not mention the demand for skilled labour. So, we classified as low.

-Quality of effluent and sludge (removal of pollutants) and environmental concern: examples of released contaminants during sewage sludge combustion: organo-metallic compounds and volatile heavy metals [141] and SO_2 emissions [203]; the fly and bottom ashes from sewage sludge combustion can be incorporated into cement clinker or to return to kiln system again as raw material [99];

reduction in sewage sludge volume, reduction in fossil fuels consumption and raw-material consumption: Rodríguez et al. [145]; reduction of CO_2 and NO_X emissions [204].

5.2. Economic indicators

-Investment costs: data from Xu et al. [148] in China, depending on the processing route adopted. In the first route (11,704 EUR), the sludge is added in the wet form (with humidity <80%) directly in the oven from a transition chamber, with the aid of special pumps. In the second route (15,305 EUR), the sludge is dried by direct thermal drying (humidity <30%, using the residual heat from the factory) and added to the precalciner with the aid of a plate chain conveyor. In the third route, (more expensive), the sludge entries into the process with humidity range <35% or <10%, passing through indirect thermal drying and is added to the precalciner by means of plate chain conveyor [148]. Rulkens [149] states that for co-processing of biosolids, no major modifications are needed, which eliminates the need for large investments.

-Operation and maintenance costs: first data includes CAPEX and OPEX cost for cement kiln use of dried sludge, based on Bertanza et al. [150]; the second data refer to costs for management of cement co-incineration from Kacprzak et al. [126] in Germany; unit refers to euro per ton of sludge (considering dry greater than 85%).

-Revenue from recovery: data about reduction in operation costs are from Andreoli et al. [93]; data about savings are from Zabaniotou and Theofilou [151]; the cost related to fuel for cement manufacturing varies from 20-25%, so the replacement of conventional fuels (e.g. co-processing with alternative fuels) can reduce significantly production costs [198]; reduction in 66% of fossil fuels consumption in cement production, and the use of ashes provided a reduction of up to 14% of raw-materials consumption (e.g. limestone and iron ore) for clinker production [145].

-Logistics (necessary changes): adaptions to kiln exhauster [152]; transport of biosolids, dosing, and feed adaptions [99, 100]. Sludge drying facility could be located inside the WWTP.

5.3. Societal indicator

-Acceptance: high, based on Pries [100] who interviewed cement industries in Brazil about the use of sewage sludge for co-processing, and all of them considered sewage sludge adequate for their production process. The only concern reported was with pathogens due to the health of their employees. Acceptance is not considered relevant for this scenario since it does not affect directly the local population.

5.4.Institutional and political indicator

-Accordance to policies and legal requirements: Related legislations about co-processing at national level in Brazil (CONAMA n.499, resolutions 316 and 436) determine standards for emissions (e.g., persistent organic pollutants and other atmospheric pollutants) in co-processing in cement factories, and other criteria; and at state level (standard P4.263-CETESB and resolution SMA n. 38) [193, 194, 195, 197, 206]. They do not contain specifications for sewage sludge in co-processing.

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water
MDPI

Supplementary Material

A Framework for Sustainable Planning and Decision-Making on Resource Recovery from Wastewater: Showcase for Sao Paulo Megacity

Mariana C. Chrispim [1,2], Fernanda de M. de Souza [2], Miklas Scholz [1,3,4,*] and Marcelo A. Nolasco [2]

Supplementary Material 4: Further explanation to Figure 5.

1. Table A.

Quantitative and qualitative values considered for elaboration of Figure 5.

Category	Indicators	A	B	C	D
Technical and Environmental	Recovery potential	0.53 ton/day	2.025 ton/day	9,937.05 kWh/day	166,607.47 kWh/day
	Technology maturity	5	9	9	9
	Resource utilization	middle	low	80,263.5 kWh/y	12,620,927.30 kWh/y
	Need for additional skilled labour	high	middle	middle	low
	Positive environmental effect	moderate	significant	significant	moderate
	Quality of final product	very high	high	n.a.	n.a.
Economic	Investment cost	7.2 EUR/kg	0.2 EUR/kg	572,161.5 EUR	1,623,871.2 EUR
	Operation and maintenance cost	311,038.4 EUR/year	22,546 EUR/year	23,488.9 EUR/year	included in the investment cost
	Revenue from recovery	0.65 EUR/kg	0.015 EUR/kg	207,792.9 EUR/year	63,360 EUR/year
	Logistics	middle	high	middle	low
Societal	Acceptance	high	middle	high	high
Institutional and political	Accordance to policies and legal requirements	possible but insufficient	sufficient	sufficient + incentives	sufficient

Notes: n.a.: not applicable; A: Phosphorus (Struvite); B: Nutrients and organic matter (Sewage sludge co-composting); C: Energy (Biogas from co-digestion with food waste); D: Energy (Co-processing of sludge in cement industries).

The assessment considered the application of the scenarios in the studied WWTP.

-Recovery potential: The assessment was based on quantitative values estimated and displayed in Table 6. For scenario C, the average between 8,877.7 – 10,996.4 kWh/day was considered. Green values were attributed when there is a higher value of recovered resource.

-Technology maturity: Based on TRL. Green values for scenarios B, C and D due to highest TRL and intermediate (yellow) to scenario A, due to lower TRL.

-Resource utilization: Scenarios A and B are compared in terms of energy and reactants consumption. Scenario A was classified as middle because of more consumption of reactants (e.g. $MgCl_2*6H_2O$). The lesser the resource utilization the more favourable the solution is. For scenarios C and D, we considered only the electricity consumption. In scenario C, the electricity consumed by Otto cycle engine would be 219,9 kWh/day or 80,263.5 kWh/year. For scenario D the electricity consumption (12,620,927.30 kWh/year) refers to sludge drying process and was estimated. Considering that the sludge should have 30% of water after drying, the amount that needs to evaporate is 41.66 tons of water from the initial moisture (66.9% of 112.9 tons), and the mean energy demand is 850 kWh/ton of water (based on Flaga [209]).

-Need for additional skilled labour: Based on Table 6. Low (green), middle (yellow), high (red), because the more the need for skilled labour the more difficult and expensive to implement the solution.

-Positive environmental effect: scale: significant (green); moderate (yellow); insignificant (red). For Scenario A we attributed moderate while B is significant because composting has more benefits in terms of avoided emissions, no need for disposal of sludge, reduction of global warming, than struvite recovery scenario. Both scenarios contribute to reduce eutrophication. Scenario C: significant, because would reduce 50-60% of GHG emissions and the digestate could be used in agriculture. Scenario D was classified as moderate, because of possibility and uncertainties related to emissions of pollutants during burning and reduction of GHG emissions.

- Quality of final product: scale from 1 to 5- very low (red) to very high (green). Scenario A was assessed as very high (5) and B high (4) because there is a concern related to pollutants or heavy metals in the compost, which is not associated to struvite product. As compost contains micronutrients and organic matter, both scenarios were classified as favourable in this indicator.

-Investment cost: Scale: high (red), middle (yellow), low (green). Scenario A assessment was based on the average of the values in Table 6. Scenario B was based on value from Kacprzak et al. [126]. Scenario A was classified as middle because requires much higher investment costs than scenario B. Regarding scenarios C and D, both were considered as middle. In Scenario C, the authors considered the average between 750,000 EUR and 394,323 EUR, (Table 6), value within the range 500 thousand to 1 million euros. For scenario D, we considered 25 EUR/tonnes of dewatered (mean value from Bertanza et al. [150]. Considering 112.9 tonnes per day, it results in 1,030,212.5 EUR/year-including capital and operation expenditures. The authors did not find the operation costs separately.

-Operation and maintenance cost: scale: low (green), middle (yellow), high (red). For scenario A, the value was calculated based on 1.6 EUR/kg P rec (Table 6) times the recovered P per day (532.6 kg). Scenario B was based on data from Visentin [125]. The calculations for scenario C and D are as follows. For scenario C: the estimated cost considered repair and maintenance costs, biogas treatment and other maintenance costs (Table 6 values) 23,847.9 EUR/year. We assumed these costs as higher due to the additional costs for organic waste pre-treatment (50 EUR/ton) (Scenario C); the authors do not know the amount of food waste would be co-digested per day since it depends on its characteristics, but in another Brazilian WWTP with co-digestion with a similar capacity to the WWTP ABC, the food waste amount per day was 120 tonnes [210], which gives a rough indication of a large amount that requires pre-treatment. For scenario D, operational costs will depend on the drying process used to dry the sludge, we classified as middle due to the possibility of high electricity demand for drying.

-Revenue from recovery: scale: low (red), middle (yellow), high (green). Scenario A and B: Considering the price per kg of product, struvite is more valuable than compost (Table 6), however considering the estimated amount produced per year, the potential revenue would be higher for scenario B than scenario A. The daily amount of produced sludge is much higher than supernatant flow. So, we considered scenario B as green and A as yellow. Scenario C: based on the mean value (Table 6). Scenario D: based on data from Hannoun et al. [199], savings of 8 EUR/h x 7920 hours of operation of cement kilns.

-Logistics (necessary changes): low (green), middle (yellow), high (red). The lesser the necessary changes the more favourable the scenario is. Scenario B was considered as red because it demands more space (e.g. for composting plant, storage of compost) and partnership with organic waste providers/generators. The assessment of scenarios C and D considered the necessary changes presented in Table 6 and SM3.

-Acceptance: scale from 1 to 5 (no accepted to highly accepted); 1 and 2 (red), 3 (yellow), 4 and 5 (green). The more the social acceptance the more favourable the scenario is. Based on Table 6 and SM3 information.

-Accordance to policies and legal requirements: scale: possible but insufficient (red); sufficient (yellow), sufficient + incentives (green).

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