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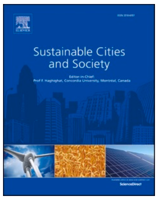

Evaluating the impacts of nutrients recovery from urine wastewater in Building-Integrated Agriculture. A test case study in Amsterdam

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ABSTRACT

Recent studies concerning the integration of agricultural practices in cities demonstrated that Urban Agriculture (UA) can boost new sustainable urban developments. New technologies allow to integrate soil-less cultivation in- and on- mixed-use buildings, creating new synergies between the built environment and the urban food system. Accordingly, resource flows from buildings are an untapped opportunity for the creation of circular urban metabolisms that rely on recycling waste as input for food production systems. On this trail, this research work focuses on evaluating the feasibility of using urine and greywater streams as nutrient solution in a theoretical model of Building-Integrated Agriculture (BIA) located in Amsterdam. Results showed that it is feasible to use urine and greywater as nutrient solutions (NS). However, treated urine showed higher concentration of macronutrients compared to fertilizer recipes found in literature, and therefore needed to be diluted with increasing amount of greywater to match either N or P concentration. Accordingly, P deficiencies in the plants or excessive N concentration were found in the final wastewater-based NS. Future research is highly recommended to assess the quality of plants grown in BIA systems as well as the possible content of harmful viruses and bacteria in the harvested produce.

1. Introduction

In our society, cities are the greatest food sink (Scialabba, 2015). Today, even if urban environments only cover 3% of the inhabited land (UN, 2020), cities absorb more than 70% of the whole food supplies produced for humans, with this number bound to increase up to 80% by 2050 (Ellen MacArthur Foundation, 2019). Accordingly, most of the food produced in the World is processed and consumed in urban areas, generating high amounts of organic waste in the form of discarded food, byproducts, or sewage (Pozzer et al., 2017). Indeed, within the current linear model, less than 2% of these valuable wasted resources are reused and cycled back as further inputs for the food system (Ellen MacArthur Foundation, 2019). This is because the places of production and the places of consumption are not contiguous, making it extremely difficult for recovered nutrients to find their way back through the food chain (Béné et al., 2019).

The importance of nutrients' recovery is crucial, given that today nutrients' extraction for agriculture is among the most underestimated human polluting activities (Naidu et al., 2021). Phosphorus (P) and Nitrogen (N) are essential and irreplaceable elements in food production (Tervahauta, 2014) and from the past century have been extensively used to increase crop yields. The large application of chemical fertilizers results in pressing environmental problems. P fertilizers extraction from phosphate rocks is causing landscape degradation and a high amount of CO_2 emissions due to mining processes and transport (Schroder et al., 2010). Concurrently, N fertilization is associated to large environmental impact due to the excess reactive nitrogen released to both soil and water resources (Holmes et al., 2019). Besides, as urbanization grows, buildings and citizens are also releasing a larger and more diversified amount of waste streams (Shahrokni et al., 2015).

As a result, environmental and public health problems may arise from the insufficient provision of sanitation and wastewater disposal facilities (Tervahauta, 2014). Tertiary and final wastewater treatment is then required to meet environmentally-safe discharge standards, and while most of them largely rely on chemicals, alternatives that use new biological treatment technologies are increasingly developed and available (Magwaza et al., 2020a). To this end, hydroponic systems have been identified as possible alternative technologies that can be integrated with wastewater treatment (Prazeres et al., 2017; Magwaza et al., 2020b). Integrating food production in urban areas could then be a solution to provide proper final wastewater treatment in cities. Furthermore, new soilless technologies (e.g., hydroponics, aquaponics, aeroponics) offer the opportunity to move part of the food production within cities, taking advantage of vacant or under-used spaces like

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rooftops, facades, squares, and interior spaces, that can actively host a diffuse, large-scale urban food production (Specht et al., 2014). Soilless and intensive production methods can therefore easily be integrated in and on mixed-use buildings with the possibility to generate new synergies between the built environment and the production systems (Tapia et al., 2021). This integration between advanced food production systems and the built environment defines a new specific subtype of Urban Agriculture, namely Building-Integrated Agriculture (BIA) (Thomaier et al., 2014). In this scenario, BIA may benefit from recovering nutrients from wastewater in urban areas, replacing synthetic fertilizers. In this sense, this paper hopes to contribute to the discussion concerning the design of future sustainable and resilient cities, assessing the possibility of maximize wastewater recovery, treatment, and recycling for soil-less food production in dense urban areas. In the hydroponic wastewater treatment, nutrients-rich water coming from municipal activities can be used to fertilize plants that in addition act as wastewater final treatment to meet discharge/reuse standards (Udert et al., 2012). However, domestic wastewater is composed of different water streams flowing out from residential buildings, including greywater from washing activities, blackwater, kitchen refuse, and urine from toilets (Tervahauta, 2014). Accordingly, each waste stream has different characteristics that make it more suitable for different applications in integrated food production systems. Today, resource recovery from wastewater is possible thanks to localized, source-separated sanitation systems, also known as new sanitation, that keeps streams separate and concentrated minimizing mutual contamination and dilution of streams, which facilitates nutrient recovery (Wielemaker et al., 2018). Nutrients can be recovered primarily from blackwater, while greywater serves as an alternative water source for irrigation. Blackwater can be further divided into urine and feces using urine-diverting toilets or urinals. Urine contains most of the nutrients while feces contain most of the organic matter which make them preferably usable for composting and soil conditioning (Wielemaker et al., 2018). Since urine contains the greatest fraction of usable nutrients for hydroponics it makes sense to divide urine from feces and kitchen refuse to collect as many usable nutrients as possible (Larsen et al., 2009).. Accordingly, the present research work investigates the feasibility of combining optimized technologies for wastewater treatment with an integrated hydroponic system as tertiary treatment for wastewater recovery in residential buildings. To model flows and elaborate on quality and quantity of treated wastewater to be used as fertilizer in BIA projects, the research is applied on the specific test case of the Sluisbuurt area in Amsterdam, where a large urban regeneration process is ongoing. To our knowledge, this is the fist study that, elaborating on previous experiments and results, builds a model for large-scale wastewater recovery and reuse in urban areas through integrated hydroponic systems. Therefore, this study proposes a methodological approach that can be used by architects and urban planners to assess the feasibility of using wastewater-based fertilizer for new BIA systems, highlighting the importance of wastewater recovery for future urban food production.

2. Materials and methods

This study contributes to the creation of a theoretical model for a Building-Integrated Agriculture (BIA) residential district in Amsterdam using treated domestic wastewater as nutrient solution in the integrated hydroponic systems. To this end, the research analyzed the best available technologies for nutrient extraction from urine and Nature Based Solutions (NBS) for greywater treatment. The content of nutrients extracted from urine and the recovered greywater were used to compose the nutrient solution fed to the crops in the integrated hydroponic production. Mathematical models were then used to compare the concentration of nutrients in the wastewater-based fertilizer with commercial fertilizers commonly used in the selected crops. The study therefore quantifies wastewater flows in the BIA project, assessing the potential efficacy of wastewater-based fertilizer.

2.1. Assumptions and theoretical background

The first step of this study was to assess the best available on-site urine and greywater treatments. To this end, an extensive literature review and direct interviews were conducted. The extrapolated data were later used as assumptions to determine the quantity and quality of nutrients and clean water extracted from the domestic wastewater in the Sluisbuurt area. Defining the assumptions was crucial to determine the dimensions of the production systems as well determine the methodological approach in the calculation of all the variables of the mathematical model. Results may change based on social and geographical contexts. The choice to operate in a given context is therefore crucial to obtain the input parameters needed for the design of the BIA model. In this scenario, developing a broad methodology is fundamental to adapt the design principles to possibly different inputs provided by different municipal plans or geographical and climatic contexts. This way, the methodological approach proposed in this paper is intended as a series of operational processes for the development of similar BIA projects. Therefore, the methodology leading to the results presented in this paper can be easily replicated in different locations and scenarios building on their site-specific assumptions. Accordingly, the proposed methodology unfolds as follows (Fig. 1):

2.2. Constructing the framework of the test case study

The area selected for testing the feasibility of hydroponic wastewater treatment systems integrated with BIA projects was located in Amsterdam in the Sluisbuurt district. The population of Amsterdam has grown rapidly in recent years with an average annual increase of 10,000 inhabitants since 1984 (World Population Review, 2022). In this scenario, the municipality of Amsterdam has developed specific strategies to facilitate this growth and at the same time reduce pressure on the housing market. The goal is to enable the construction of 52,500 homes within the city boundaries by 2025. To deal with this concern, several areas were identified, as summarized in a medium-term municipal development strategy "Setting the course for 2025 - Space for the City" (Gemeente Amsterdam, 2016). This strategy focuses on increasing the densification of the urban environment with attractive and diverse urban planning. The area selected for this research is part of the development strategy and is located on a waterfront in the northwestern part of the city within the A10 highway ring, overlooking the IJ river and the inner city. The new plan for the Sluisbuurt area aims to build around 5,500 homes for about 11,000 inhabitants (Gemeente Amsterdam, 2017), in addition to a maximum of 100,000 m^2 of non-living green areas, consistently with the objectives described in the Amsterdam Structural Vision 2040 (Gemeente Amsterdam, 2011). Due to the high density of the Sluisbuurt neighborhood, the municipality provided specific guidelines concerning the sustainability and livability of the built environment such as: i) improve water resiliency; ii) make use of abundant green roofs and facades; iii) foster a local circular economy; and iv) improve local waste management. In this sense, the Sluisbuurt area presents the essential characteristics to propose a BIA project with integrated wastewater recovery. The area was selected – in collaboration with the municipality of Amsterdam (Gemeente Amsterdam) and the Horticulture Greenhouse Department at Wageningen University & Research, in 2020. It included an experimental study on one of the Sluisbuurt clusters that currently were under development. This community was chosen as the Municipality planned to destine part of the development plan (10% of the total surface) for construction experimentation. The hereby presented research has been designed to operate in the framework of this 10%, analyzing the possible impacts of on-site hydroponic wastewater treatment in Cluster 2 (Fig. 2). The selected area of intervention is characterized by the presence of five residential buildings blocks, each hosting commercial activities at the ground level and residential apartments in the upper floors.

Data referring to the total surface area and the total Rooftop surface

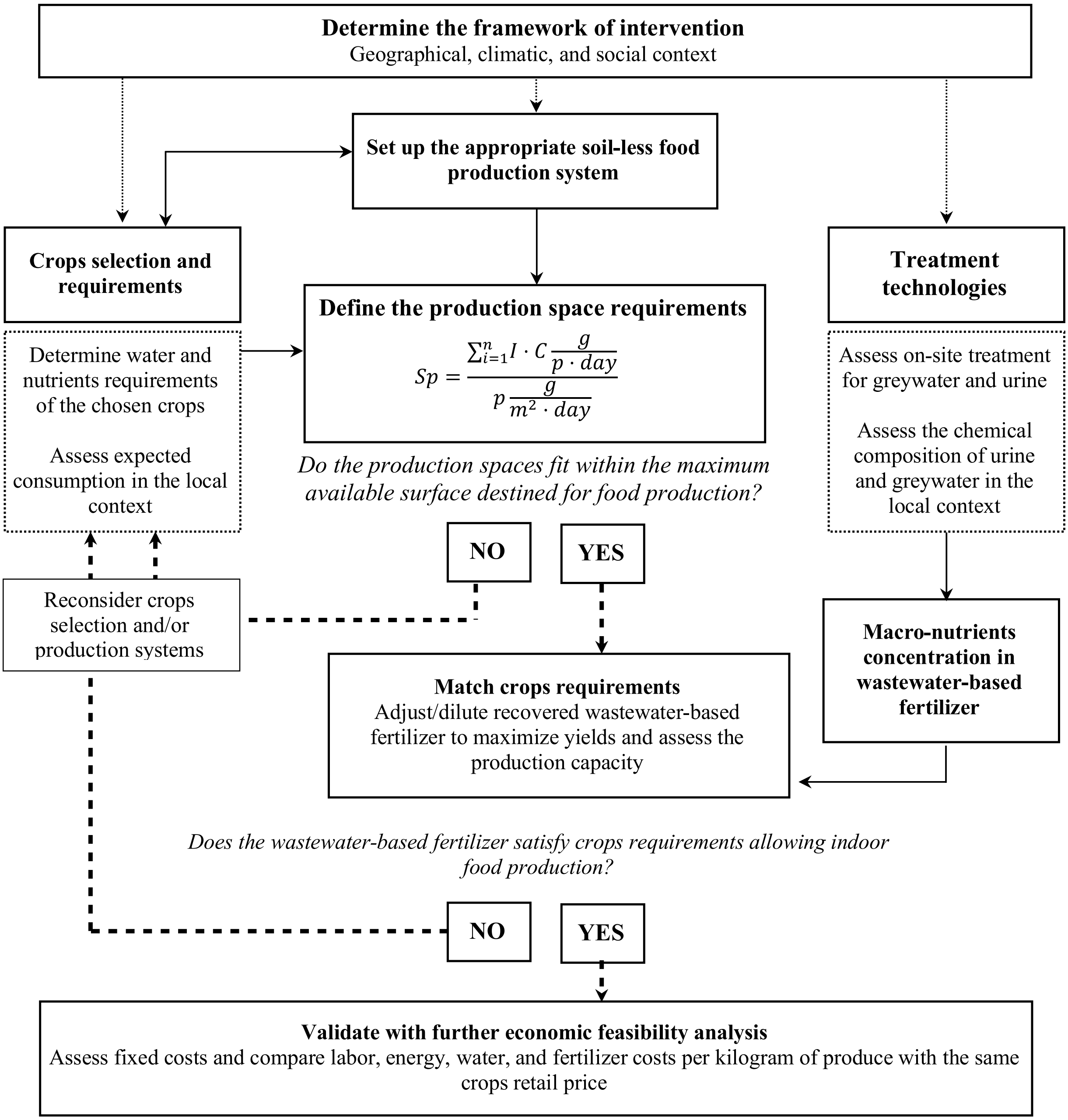


Fig. 1. Proposed methodological approach

are indicated in the Sluisbuurt Construction Plan, available on the Municipality of Amsterdam online website (Gemeente Amsterdam, 2017).

2.3. *Determine wastewater treatment technologies*

2.3.1. *On-site systems for nutrients recovery from urine*

Today, decentralized wastewater systems present some advantages over centralized systems. Green buildings initiatives have started to promote the use of decentralized wastewater systems (Capodaglio et al., 2017), generally in the form of water recycling and nutrients recovery, to reduce overall water use and toward the aim to reach zero discharge goals (Radini et al., 2021). Accordingly, several studies have been recently conducted to extract nutrients from the urine waste stream. Different technologies have been developed, ranging from struvite precipitation to recover Phosphorus (P) (Liu et al., 2016; Siciliano et al., 2020) coupled with ammonia stripping to recover Nitrogen (N) (Zhang, 2018; Yang et al., 2015) to nitrification (Etter and Udert, 2015) and distillation (Udert and Wächter, 2012). The research presented here used and adapted the model developed by the EWAG research center in the framework of the VUNA project (Valorization of Urine Nutrients for Africa), that successfully managed to extract macro and micro-nutrients from stabilized urine through nitrification in a Moving Bed Biofilm Reactor (MBBR) with further distillation (Etter and Udert, 2015). The experiment was later on successfully replicated in South Africa (Magwaza et al., 2020b) to harvest tomatoes using the Nitrified Urine Concentration fertilizer from collected urine. Results showed that through the Nitrification process >99% of N and 100% of P and K are recovered (Etter and Udert, 2015).

2.3.2. *On-site Nature Based Solutions (NBS) for greywater treatment*

Domestic greywater represents about 95% of the total volume of buildings' wastewater. Accordingly, it has been increasingly used as an alternative water source to reduce potable water demand and to alleviate pressure on sewage systems (Radingoana et al. 2020). Since light

Characteristics of Cluster 2	Dimensions
Tot. Surface area	1.9 ha
Tot. Households	390
Nr. Building blocks	5
Expected inhabitants	780-860
Tot. Rooftop surface (=GFA)	13.000 m2

Fig. 2. Selected cluster in the Sluisbuurt area (highlighted with the red dotted rectangle) and its characteristics

greywater is the least polluted of domestic wastewater streams (Giresunlu et al., 2016), it requires minimum treatment and is mostly suited for on-site treatment and re-use schemes. Currently, many on-site technologies are applied for greywater treatments such as filters, fixed-film reactors, rotating biological reactors, membrane bioreactors, sequencing batch reactors, and wetland systems (Fowdar et al., 2017). The development of these technologies allowed to minimize risks associated with pathogens and bacteria in treated greywater (Vuppaladadiyam et al., 2019). Nonetheless, in recent years, new biological treatments, also known as Nature-based Solutions (NBS) for greywater treatment, have been developed with the advantage that they can operate under low energy and low maintenance requirements (Eriksson et al., 2002). In this regard, living walls and green roofs represent viable solutions for on-site greywater treatment as they can directly be integrated with buildings improving their aesthetic and overall sustainability (Coma et al., 2017). Recent researches have targeted the best design configuration for a green wall capable to efficiently treat domestic greywater, in Australia (Fowdar et al., 2017; Prodanovic et al., 2020). In particular, for the sake of the current research, the configuration of the green wall to be used was designed building on the study by Prodanovic et al. (2020). It consisted of a modular pot design green marketed both in Australia and UK (Gro Wall 4.5, Atlantis Corporation, Chatswood, New Wales, Australia) consisting of individual containers filled with media hosting a single plant. The configuration consisted in two-levels pot design with greywater percolating from the top and collected at the bottom. The reported configuration consistently reduced pollutants content in greywater and is therefore a usable system for on-site greywater treatments complying with national and international reuse guidelines (Epa Victoria, 2003; US Epa, 2012; WHO, 2006). More specifically, in former experiences, the green wall allowed for pollutants removal of 98% of Total Suspended Solids (TSS), 94% of Chemical Oxygen Demand (COD), 92% of Total Nitrogen (TN), and 46% of Total Phosphorus (TP), although requiring for further disinfection for *E. coli* (Prodanovic et al., 2020).

2.4. Amsterdam domestic wastewater characteristics and composition

The quantity and quality of domestic wastewater used in the proposed theoretical model was extrapolated by wastewater lab analyses conducted in Wageningen University & Research in 2014 (Tervahauta, 2014). Based on these analyses, supposing that new sanitation systems were installed in all five buildings blocks in Cluster 2 using gravity urine-diverting toilets, it is expected that the system may collect up to 5 L person^{-1} day^{-1} combined of urine and flushing water (Tervahauta, 2014). The final composition of Dutch domestic wastewater has been reported in Table 1 (Tervahauta, 2014).

2.5. Food productions systems assumed for Cluster 2 in the Sluisbuurt area

To better assess the efficacy of the integrated hydroponic wastewater treatment, it was decided to use two different production methods: an integrated Rooftop Greenhouse (iRTG), and a Plant Factory with Artificial Lighting (PFAL) for indoor production. The adoption of both systems was functional to allow comparative assessment of functionalities provided by the hydroponic wastewater treatment. Both growing systems integrate hydroponic cultivation, but they are substantially different as the former uses solar energy to promote plants' photosynthetic processes, while the latter uses artificial light provided by LEDs to substitute solar radiation, as it take place in opaque compartments insulated from the external environment (Proksch, 2016). Considering the objectives of the project, it is important to choose the features that best fit the capacity of the system to maximize the production and, at the same time, to absorb nutrients from the wastewater streams. The design of the enclosures of the iRTG follows the typical Dutch venlo-style greenhouses (Baeza et al., 2019; Proksch, 2016), while the PFAL consists of an air-tight structure for indoor production (Kozai and Niu, 2020; Graamans et al., 2020) where crops are cultivated on five-layers trays

Table 1
Amsterdam's wastewater characteristics

Parameter	Unit	Urine	Grey Water*	Unit
Volume	L person^{-1} day^{-1}	1.4	88.6	L day^{-1}
COD	g person^{-1} day^{-1}	11.0	52	g day^{-1}
BOD	g person^{-1} day^{-1}	5.5	27	g day^{-1}
TSS	g person^{-1} day^{-1}	40.0	55	g day^{-1}
TN	g person^{-1} day^{-1}	9.0	1.2	g day^{-1}
NH4+ - N	g person^{-1} day^{-1}	9.0	0.1	g day^{-1}
TP	g person^{-1} day^{-1}	0.8	0.4	g day^{-1}
K	g person^{-1} day^{-1}	2.8	0.8	g day^{-1}

COD: Chemical Oxygen Demand; BOD: Biochemical Oxygen Demand: TSS: Total Suspended Solids; TN: Total Nitrogen; NH4+ - N: Nitrogen expresse as Ammonium; TP: Total Phosphorus; K: Potassium.

* Total daily load of greywater 88.6 L person^{-1} day^{-1} does not consider 5 L person^{-1} day^{-1} of urine flushing activities. Flushing activities are not considered since they are not recovered for greywater treatment.

(Supplementary Material).

2.6. Selecting the crops for Cluster 2

Based on recent studies (Orsini et al., 2020; Kozai and Niu, 2020; Paucek et al., 2020; Magwaza et al., 2020b) the crops selected for Cluster 2 are the most commonly used in greenhouses and PFALs, and available data include yields as well as water and nutrient requirements. Accordingly, fruity vegetables (e.g., using data from bell peppers) will be produced in the greenhouses, while leafy vegetables (using data referred to lettuce crop) in the PFAL (Kozai and Niu, 2020). Since the crops have different planting densities and cycle lengths, the productivity was calculated as g m^2 day^{-1}. Data concerning the production capacity of the two systems refer to several recent practical experiments conducted in the Experimental Greenhouses and in the recently constructed Alma V-Farm, a state of the art Vertical Farm, both located at the Department of Agricultural and Food Sciences of the University of Bologna. Expected yields, crops' water use efficiency, and water requirements are included in Table 2.

2.6.1. Expected consumption of fruits and vegetables in the Sluisbuurt area

Based on the indications provided by the Dutch National institute for Public Health and Environment (Van Rossum et al., 2016), the expected consumption of the selected crops in Cluster 2 was divided into: i) 220 g $person^{-1}$ day^{-1} of Leafy Greens (*GREENS*) and ii) 180 g $person^{-1}$ day^{-1} of Fruit Vegetables (*FRUITS*).

2.7. Setting up the calculations to size the productions spaces in Cluster 2

The definition of the adequate dimensions of the two food production systems was obtained by combining the potential food productivity with the actual food requirements. Namely, the total production of Cluster 2 was obtained by multiplying the total cultivated surface times the production capacity of each selected crop. On the other hand, the expected consumption that takes place in the same area was obtained by multiplying the total number of inhabitants by the expected consumption per capita (Equation 1):

$$D = Sp\,x\,P \,/\, \Sigma_{i=1}\,x\,C \tag{1}$$

Where:

- ***D*** is the total fruit and vegetable demand. Per ***D=1***, 100% of the total demand of a certain crop or food typology is satisfied.
- ***Sp*** in the total surface of each food production system expressed in m^2.
- ***P*** is estimated based on existing literature and represents the expected average production capacity of each selected crop, expressed in g m^{-2} day^{-1}.
- $\boldsymbol{\sum_{i=1}}$ is known and represents the total number of inhabitants living in the targeted urban area.
- ***C*** is known and represents the desirable consumption of certain fruits and vegetables per capita.

Table 2
Selected crops reported yields and requirements

	Fruity vegetables	Leafy greens (e.g., lettuce)
Production method	Ventilated rooftop greenhouse with artificial light	PFAL on 5 levels trays.
Expected yields (g m^{-2} day^{-1})	110 (Montero et al., 2017)	1,000 (Pennisi et al. 2019)
Water use efficiency (g FW L^{-1} H_2O)	71 (Torellas et al., 2012)	80 (Pennisi et al., 2019)
Water recovery from dehumidification	NA	76% (Kozai and Niu, 2016)
Water requirements (L m^2 day^{-1})	1.55 (Calculated)	12.5 (Calculated)
Nutrients requirement (commercial fertilizer recipe)	N - NO_3- = 21.1 mM (Paucek et al. 2020) **P-H_2PO_4 = 1.56 mM (Paucek et al. 2020)** **K = 10.8 mM (Paucek et al. 2020)**	**N-NO_3— = 12.4 mM (Pennisi et al. 2019)** **P = 1.1 mM (Pennisi et al. 2019)** **K: 7.2 mM (Pennisi et al. 2019)**

* Fresh Weight

Building on the analysis of the National Food-Based Dietary Guidelines (Kromhout et al., 2016) and a number of references on the desired fruit and vegetable consumption quantity (European Heart Network, 2017; Pretorius et al., 2021), the total desired consumption was assumed to be 400 g $person^{-1}$ day^{-1} of fruit and vegetables. Besides, technical reports illustrating local diets were used to further identify specific quantities for specific vegetable crop typologies. Within The Netherlands, the document "The Dutch diet" written by the national institute for Public Health and Environment (Van Rossum et al., 2016) reported that 36% of the total vegetable consumption is covered by Fruits Vegetables; 38% by leafy greens including salad and cabbage, and 9% by root vegetables such as carrots and parsnip. The remaining percentage (17%) is represented by mushrooms, stalk vegetables, onions garlic and leek. Knowing the dietary demand for each vegetable, equation [1} can be inverted to get the required surface to fully/partly cover that, for each combination of vegetable and growing system. Assuming D=1 all data is known except for the required dimensions of the production spaces "***Sp***" that can therefore be calculated for each combination of growing system and vegetables**.** Accordingly, the quantification of the required surface was calculated as described in Equation 2:

$$Sp = \sum_{i=1} x\,C \Big/ P \tag{2}$$

2.8. Calculating macro-nutrients concentration in wastewater-based fertilizer

Nutrients requirements (N, P and K, Table 2) were converted from mM to mg L^{-1}. Total water requirements can be obtained from daily water needs in the two cultivation systems (L m^{-2} d^{-1}) and their cultivated cropped surface (m^2). Accordingly, it is possible to calculate the concentration of nutrients in the treated wastewater effluent by dividing the total mass of N, P, and K both in urine and greywater by the total water requirements of each crop. For instance, to calculate N concentration in the treated wastewater:

$Nnc_{(mg/L)} = [(Nu_{mass} + Ngw_{mass})/W_{req}]x1000$Where:

- **Nnc** is the Nutrient concentration of Nitrogen
- **Nu_{mass}** and **Ngw_{mass}** are the the total mass of Nitrogen contained in urine and greywater expressed in g/day
- **W_{req}** is the water requirements of each specific crop

To calculate the mass of N, P, and K, the total content of each element in urine and greywater was multiplied by the daily load of urine and greywater that will be provided to the production system and then divided by the total initial volume of respectively urine and greywater. For instance, the mass of N contained in urine and greywater used in the previous equation was calculated as follow:

$$Nu_{mass} = TNuxDLu/Vu$$
$$Ngw_{mass} = TNgwxDLgw/Vgw$$

- **TNu** and **TNgw** represent the mass of the Total Nitrogen found in urine and greywater as reported in Table 5.

- **DLu** and **DLgw** are the daily load of urine and greywater provided in each of the two systems
- **Vu** and **Vgw** is the total daily volume of urine and greywater reported in Table 5.

3. Results and discussion

3.1. Assessing the production capacity of the system

Considering the characteristics of Cluster 2 (previously reported in Fig. 1) with a maximum capacity of 860 inhabitants, vegetables and fruits production needed to satisfy the local daily food demand would be 189 kg day^{-1} of *GREENS* and 155 kg day^{-1} of *FRUITS* (a total of 344 kg day^{-1} of fruits and vegetables). Based on equation [2}, the minimum cultivated surface for *GREENS* in the PFAL is 946 m^2. Concurrently, a minimum surface of 1410 m^2 is needed to produce enough *FRUITS* in the iRTG. Since *GREENS* are produced on 5 tiers inside the PFAL, the total spatial footprint needed for *GREENS* can be reduced to only 189 m^2. Considering the corridors between the trays and the space required for installations and machineries, it is assumed that the total dimension of the PFAL would be 3 times bigger than the cultivated surface. This assumption is based on the floor-plan of a similar Vertical Farm located in Bologna in the Department of Agricultural and Food Sciences. Accordingly, the total surface occupied by the PFAL to satisfy the demand for *GREENS* in Cluster 2 is 570 m^2. Concerning *FRUITS*, the minimum area required to satisfy the local food demand largely fits within the total rooftop available surface (13,000 m^2) (Fig. 3), and can therefore be partially enlarged to increase the productivity of *FRUITS*. Nonetheless, there are some limitations concerning rooftop usage described in the Municipality masterplan (Gemeente Amsterdam, 2017). Accordingly, one third of the total rooftop surface has to be destined to green roofs, while another third must host extensive solar production systems with photovoltaic (PV) panels destined to the residential buildings and commercial activities of the Cluster. Therefore, the remaining third of the surface can potentially be assigned to food production in iRTGs (approximately 4,330 m^2) without entering in competition with the solar production system and the extensive green roof. If distributed equally over the five building blocks, each block would host an iRTG of 870 m^2 gross surface. Considering that in a typical Dutch greenhouse 20% of the gross surface is destined to machineries and corridors, the final cultivated surface of each iRTG would be around 705 m^2. Accordingly, summing the total production of the iRTGs and the PFAL, Cluster 2 would be able to satisfy about 160% of its food demand producing 577 kg day^{-1} of fresh fruit and vegetables (387.8 kg day^{-1} *FRUITS* and 189.2 kg day^{-1} *GREENS*) as reported in Fig. 3.

3.2. Characteristics and composition of domestic wastewater in Cluster 2

Based on the values reported in Table 1 that refers to the average wastewater composition of the city of Amsterdam, it is possible to calculate pollutants concentration of the wastewater in Cluster 2, considering a total population of 860 inhabitants (Table 3).

3.3. Design of the on-site urine recovery treatment system

According to the available literature, both struvite precipitation and nitrification are functional technologies for urine treatment and nutrient extraction. When ammonia stripping is used, almost all nitrogen can be recovered from source-separated urine, and a nearly complete recovery of ammonia is also possible. However, the reported needs for strong energy inputs are challenging for small decentralized reactors (Siegrist et al., 2013), and ammonia stripping is therefore not recommendable for small urban compounds like Cluster 2 in the Sluisbuurt area. On the other hand, the MBBR reactor (Etter and Udert, 2015) used in the VUNA project proved to be easily scalable to treat urine and therefore was considered the best option for the treatment process in this specific test

Table 3
Urine and greywater composition in Cluster 2

Parameter	Unit	Urine composition	Greywatercomposition
Volume	L day^{-1}	**1,204**	**76,196**
COD	g day^{-1}	**9,460**	**44,720**
BOD	g day^{-1}	**4,730**	**23,220**
TSS	g day^{-1}	**34,400**	**47,300**
TN	g day^{-1}	**7,740**	**1,032**
NH4+ - N	g day^{-1}	**7,740**	**86**
TP	g day^{-1}	**688**	**344**
K	g day^{-1}	**2,408**	**688**

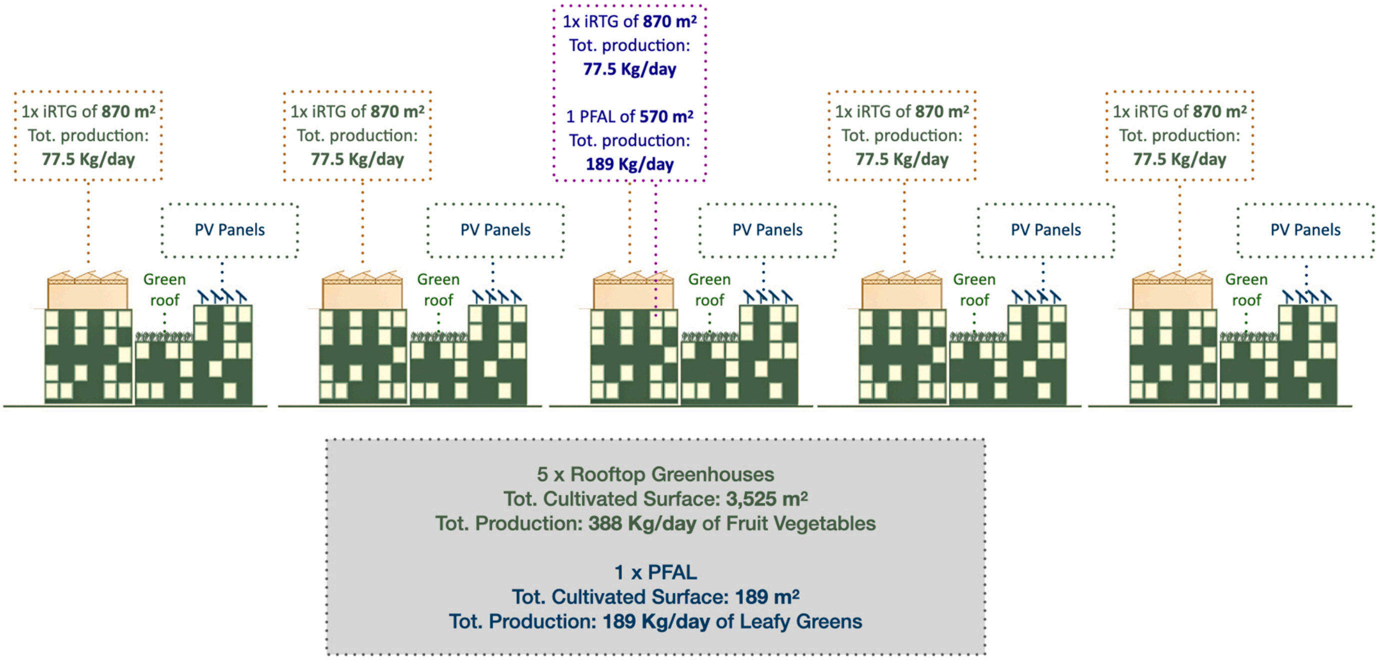


Fig. 3. Food production conceptual distribution over the 5 building blocks in Cluster 2

case. Based on these considerations and on the urine characteristics reported in Table 3, it was possible to set up the components for nitrification urine treatment as follow (Supplementary Material):

- *2x Storage Tanks* to collect urine coming from the urine-diverting toilets installed in the buildings. Each tank was sized to collect 12.7 m^3 of urine, for a total final collection of 25.4 m^3;
- *2x Nitrification columns with integrated sludge settler* to nitrify the stored urine. Each column was sized to treat 9.7 m^3 for a total of 19.4 m^3 of urine.
- *1x stabilized urine tank* of 3.6 m^3 sized to collect the processed urine with a tolerance of 3 days;
- *3x parallel pipe units for UV disinfection*, each 1.2 m^3 (diameter: 0.2 m x length: 6 m);
- *1x disinfected urine tank* of 3.6 m^3 sized to collect the disinfected urine with a storage capacity of 3 days.

Since the collective surface occupied by the machines is approximately 40 m^2, the nitrification chamber should be at least 110 m^2 to allow for connective spaces and a small working table. It appears that the size of the nitrification chamber is relatively small compared to the size of the Cluster. The nitrification chamber can then be positioned either in the basement of one of the building blocks or in a specific designated external area (Supplementary Material).

3.3.1. Macro-nutrients concentration in treated urine-based fertilizer

Based on the water requirements reported in Table 2 and the cultivated surface of each production system (calculated in section 3.1), the total water needs of the selected crops resulted in 2,365 L day^{-1} for *GREENS* and 5,456 L day^{-1} for *FRUITS*. Despite the limited differences in total yield provided, the PFAL system benefitted from higher water use efficiency, and accordingly *GREENS* required for the lower share of water (around 30%) as compared with *FRUITS* (around 70%) (Orsini et al., 2020). Therefore, the daily load of treated urine provided to the crops can be divided accordingly (361 L $day^{-1}$for *GREENS* and 843 L $day^{-1}$for *FRUITS*). It is now possible to calculate the concentration of nutrients in the treated wastewater effluent as explained in Section 2.7 (Supplementary Material). Results are reported in Table 4:

As expected, the ratio between P and N and K and N in wastewater-based fertilizers was found to be relatively lower compared to commercial fertilizers. Nonetheless, a recent study (Magwaza et al., 2020b) demonstrated that the ionic form of both phosphorus and potassium makes it readily available for plant absorption upon application. Furthermore, N and P concentrations in urine are much higher than in the fertilizer recipes found in the literature (Orsini et al., 2020; Pennisi et al., 2019) while K is slightly higher in the leafy greens and slightly lower in *FRUITS*. Accordingly, it is necessary to lower the concentrations of N and P in the wastewater-based fertilizer to match the commercial recipe requirements. In this regard, there are two possible strategies to follow:

1. Reduce the amount of treated urine and use only the quantity needed to match the commercial fertilizer recipes. The advantage here consists in not having to increase the amount of treated greywater in the nutrient solution mixing tanks. However, the excessive nitrified urine will be discharged without going through the hydroponic treatment. Nonetheless, the high amount of treated greywater that is discharged may allow to dilute the excessive content of nutrients in the discharged urine so that the concentration of pollutants in the discharged water comply with discharge water standards.
2. Dilute the urine-based fertilizer with an increased amount of treated greywater. The advantage of this strategy is that all urine is recovered and used, but then there would be more nutrient solution than what is needed. Furthermore, increasing the amount of treated greywater in the mixing tank would increase the size of the tank and its relative weight. Thus, if the mixing tanks are positioned on the roof, next to the iRTGs, increasing the quantity of water may result in structural problems.

Based on these considerations it was decided to opt for Strategy 1, renouncing to some of the treated urine in order to better fit crops nutrients requirement. Due to the complexity of the calculation and the multiple variables of the equation (nutrients are present both in urine and in greywater), the concentrations were calculated using Newton iterative method. Accordingly, the wastewater-based fertilizer was diluted to match P concentration of the commercial fertilized (P: 34 mg L^{-1} for leafy greens and P: 48 mg L^{-1} for fruity vegetables). However, in doing so, N concentration would still be very high compared to commercial fertilizer (respectively 354 mg L^{-1} for leafy greens and 516 354 mg $L^{-1}$for fruity vegetables), while the wastewater fertilizer would present significant K deficiency. Excessive concentrations of N in the nutrient solutions may cause lower yields (Magwaza et al., 2020b). In this sense, the design of the production spaces should acknowledge the risks of using wastewater-based fertilizer investing in the flexibility of the spaces to possibly increase the dimensions of the production units. Furthermore, other concerns may arise from the utilization of the treated wastewater: in the scenario where nutrients content was diluted to match P concentrations of the commercial fertilizers, only 555 L day^{-1} of urine were used in the nutrient solution, approximately 46% of the initial load. This means that 54% of the treated urine must be either discharged or used for other applications. In this sense, further research should assess how to use the excessive treated urine to maximize fertilizer production Concerning treated greywater, only 7,266 L day^{-1} are used as irrigation water, 10% of the initial daily load, meaning that most of the treated greywater can be circled back in the buildings for non-potable activities.

3.4. Design of the on-site greywater NBS treatment

Based on the analysis of the two reported case studies, green walls (together with green roofs) have recently emerged as a feasible technology to treat wastewater in dense urban areas (Boano et al., 2020). In green walls, greywater percolates through planted pots filled with a

Table 4
Comparison of commercial and wastewater-based fertilizer in Cluster 2

Crops	Macronutrients	Unit	Commercial fertilizer recipe	Wastewater based fertilizer
Leafy greens	N	mg L^{-1}	**173.6**	**992.8**
	P	mg L^{-1}	**34.1**	**91.0**
	K	mg L^{-1}	**281**	**312.9**
	P:N ratio	NA	0.20	0.09
	K:N ratio	NA	1.62	0.32
Fruit Vegetables	N	mg L^{-1}	**295.4**	**1,004.7**
	P	mg L^{-1}	**48.4**	**92.1**
	K	mg L^{-1}	**421**	**316.7**
	P:N ratio	NA	0.16	0.09
	K:N ratio	NA	1.43	0.32

combination of granular media such as vermiculite, sand, growstone, expanded clay, phytofoam, coco coir, and perlite (Prodanovic et al., 2017). The combination of the media mix and the choice of the right plants activate the biological processes needed to remove pollutants from greywater. Due to their high aesthetic value and the limited surface they need to operate in dense urban areas, green walls present now a relevant advantage compared to other NBS systems (Masi, 2016). For this research, it was decided to use the potted design configuration (Prodanovich et al., 2020) (Supplementary Material). This choice was justified as potted green walls are easier to manage compared to the typologies of climbing walls, since it is easier to remove and substitute the pots in case of malfunctions of the systems. The reclaimed greywater can be collected from each two pots system and redirected to a single collection tank. Here, the irrigation water is fed at the top of the potted green wall and collected at the bottom. The total height of the two pots is 450 mm and the total surface is 0.1125 m^2 (0.45×0.25 m). Based on a recent study (Boano et al., 2020), it is possible to estimate the Hydraulic Loading Rate (HLR) and the Organic Loading Rate (OLR) of the proposed system. Knowing the HLR and the OLR is fundamental to determine the size of the green walls based on the volume and composition of the greywater. Reported values of HLR and OLR are respectively 382 L m^{-2} day^{-1} and 128 g COD m^{-2} day^{-1} (Boano et al., 2020). Accordingly, it is possible to calculate the dimension of the treating green wall dividing the total daily volume of greywater by the HLR, and the total COD daily mass by the OLR. As it requires a bigger surface to treat the daily organic load compared to the COD, the OLR is the limiting factor by which assessing the final dimensions of the green wall. In this case, the final dimensions of the potted green wall resulted in 350 m^2.

Considering a daily load of 76,196 L coming from all the dwellings in Cluster 2, and the reported performances of the two-layers potted green wall (Prodanovich et al., 2020), it is possible to calculate the pollutants concentration of the treated greywater and compared it with the requirements set by the European Union for its reuse in agriculture. Results are shown in Table 5:

As expected, the green wall consistently contributes to remove pollutants from greywater, complying with the new requirements established by the European Union (Regulation EU, 2020) and therefore can theoretically be safely used for both agricultural irrigation and other non-potable uses like washing and flushing. However, further investigation should be conducted on *E. coli* content and other harmful bacteria.

Considering the characteristics of the Cluster and the relatively high dimension of the green wall, it is recommended that the total dimension of the green wall would be distributed across the 5 building blocks of the Cluster. The green walls are directly connected to the greywater collection tank. Accordingly, due to the high amount of greywater flow, it is suggested to collect the greywater in each building. Accordingly, the total green wall dimension should be equally divided in each of the five building blocks, limiting the length of the pipes that otherwise had to go from the collection tanks to the green wall and back (Supplementary Material). Therefore, by dividing the total surface of the green wall by 5, each green wall would have a surface of 70 m^2. Considering that the maximum height of the building blocks given by the municipal plan is 20 m (Gemeente Amsterdam, 2017), each green wall will have a width of 3.5 m to treat 15,240 L day^{-1} of greywater (one fifth of the initial load).

In conclusion, if 15,240 L day^{-1} of greywater are collected from each building, a collection tank of approximately 16 m^3 should be installed (slightly bigger than the daily load to absorb possible daily variations). From the tanks, the greywater is pumped into the green walls where it is treated and collected in another collecting tank of 16 m^3. However, considering an average annual evapotranspiration (ET) of 525 mm $year^{-1}$ (Jacobs et al, 2010), equivalent to ca. 1.44 L m^{-2} day^{-1}, it is possible to estimate a water loss of 101 L day^{-1} in each building, accounting for 0.6% of the initial load.

3.4.1. Assessing greywater recovery for non-potable activities and discharge standards

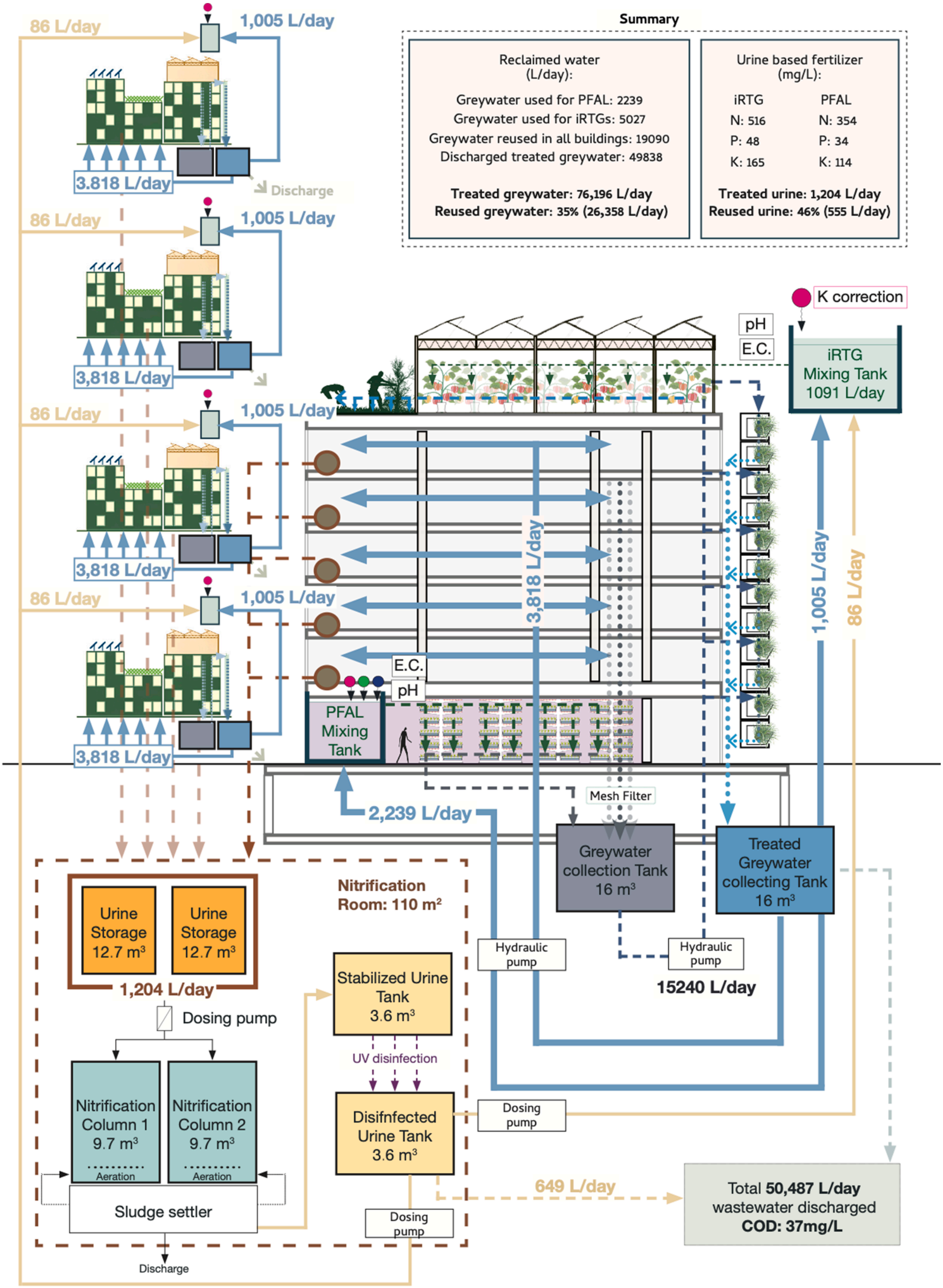
The calculated green wall surface needed to treat greywater resulted in 350 m^2, divided into five green walls of 70 m^2, one for each building block. Each 70 m^2 green wall can treat 15,240 L minus the 101 L day^{-1} water loss due to ET. Therefore, the total amount of usable reclaimed wastewater is 15,139 L day^{-1} per each wall. Based on the calculation the volume of treated greywater reused for irrigation in Cluster 2 is 7,266 L day^{-1} over the initial volume of 76,196 L day^{-1}, approximately 10% of initial amount. The remaining treated greywater (68,930 L day^{-1}) can be reused in the building blocks for non-potable uses such as washing and flushing. Considering the average Dutch composition of greywater where 5 L $person^{-1}$ day^{-1} are used for flushing and 17.2 L $person^{-1}$ day^{-1} are used for washing activities (Leal, 2010), it is possible to calculate the exact amount of water that can be circled back into each building block. Assuming that each building block has the same number of inhabitants (172) and considering the average Dutch domestic wastewater composition, it is possible to recirculate in each building 860 L day^{-1} for flushing and 2,958 L day^{-1} for laundry, equivalent to a total of 3,818. L day^{-1} of treated greywater in each building block. Thus, 19, 092 L day^{-1} of reclaimed greywater can be recovered and used in all 5 building blocks for washing and flushing. Accordingly, the total amount of daily recovered greywater used for both irrigation and non-potable activities is 26,358 L day^{-1}, 35% of the total initial greywater volume. The remaining treated greywater (49,838 L day^{-1}) can be safely discharged or stored for other utilizations. In case of discharge, it is important to calculate the final concentration of COD considering that the treated greywater effluent would mix with the excessive nitrified urine effluent that has a calculated COD concentration of 393 mg L^{-1}. When the two treated streams are mixed, the final calculated COD concentration in the effluent water is 37.5 mg L^{-1}, within the parameters set by the EU standards of 125 mg L^{-1} for safe wastewater discharge (European Commission, 2019). The final results of wastewater treatment in the BIA project developed for the Sluisbuurt area are reported in Fig. 4.

3.5. Health hazards related to wastewater-based fertilizers

The proposed irrigation method with wastewater-based nutrient solutions for vegetables and food crops may result in the bioaccumulation of heavy metals, and, at the same time, it may cause the contamination of plant products with microbial pathogens and fecal coliform. Various health problems can occur and develop due to the consumption of contaminated vegetables and the consumption of food contaminated with heavy metals. This may cause the disruption of

Table 5
Removal rates and final value of pollutant parameters in greywater

Pollutants	Influent concentration	Reference	Removal rate	Effluent concentration	Reclaimed water requirements
COD (mg L^{-1})	586.9	Calculated from (Tervahauta, 2014)	94.4	**32.9**	**BOD ≤ 10** **eq. COD ≤ 35**
TSS (mg L^{-1})	620.8	Calculated from (Tervahauta, 2014)	98.4	**9.9**	**≤ 10**
Turbidity (NTU)	167.9	(Edwin et al., 2014)	97.6	**4**	**≤ 5**
TN (mg L^{-1})	13.5	Calculated from (Tervahauta, 2014)	91.8	**1.1**	**N.A.**
TP (mg L^{-1})	4.5	Calculated from (Tervahauta, 2014)	46.0	**2.4**	**N.A.**



Summary

Reclaimed water (L/day):

Greywater used for PFAL: 2239
Greywater used for iRTGs: 5027
Greywater reused in all buildings: 19090
Discharged treated greywater: 49838

Treated greywater: 76,196 L/day
Reused greywater: 35% (26,358 L/day)

Urine based fertilizer (mg/L):

iRTG	PFAL
N: 516	N: 354
P: 48	P: 34
K: 165	K: 114

Treated urine: 1,204 L/day
Reused urine: 46% (555 L/day)

Fig. 4. Complete wastewater flows in Cluster 2

various biological processes in the body, leading to a decreased immunological defense, growth retardation, disability associated with malnutrition, and cardiovascular, neurological, kidney, and bone diseases (Pearson et al., 2010). Therefore, setting up quality control measures for the treated wastewater is critical to minimize the risk of contamination due to phytotoxic elements accumulation in the harvested crops (Magwaza et al., 2020b). Indeed, quality control has been reported to drastically reduce consumers' health problems associated with the consumption of food produced with reused domestic wastewater (Lubello et al., 2004). Concurrently, human urine demonstrated to have low heavy metal and pharmaceutical composition due to the low concentration of these elements in the food we consume (Vinnerås & Jönsson, 2002). In this sense, setting up source-separation sanitation systems is crucial to separate urine from greywater and black water, reducing to a minimum the cross-contamination between the waste streams, therefore limiting the presence of hazardous pathogens in urine-based fertilizers. Furthermore, crop contamination can be limited by selecting proper pre-treatment methods and appropriate cultivation systems (Eregno et al., 2017). Nonetheless, further investigation on the bioaccumulation of phytotoxic elements in cultivated crops with wastewater-based fertilizers is necessary to guarantee their safe consumption and prevent human diseases transmitted by reused residential wastewater.

3.6. Final outputs of the proposed BIA model

The proposed BIA model could produce roughly 160% of the total food demand of vegetables in a high-density neighborhood. On a broader scale, considering that Amsterdam will build 52,500 homes within the city boundaries by 2025 (Gemeente Amsterdam, 2016), it would be possible to produce enough vegetable food for this whole new Amsterdam population by implementing similar BIA projects on 32,800 new homes. Assuming a similar urban density of the Sluisbuurt (150-200 households per hectare) it would suffice to implement an integrated hydroponic production on 164-220 ha to feed the new 'Amsterdammers'. In this regard, the specific food production system developed for the Sluisbuurt consists in:

- *5x integrated rooftop greenhouses*. Each rooftop greenhouse is located on the roof of one building block in Cluster 2 and has a total floor area of **870 m^2**, with a cultivated surface of **705m^2**.
- *1x PFAL* with a cultivated surface of **189 m^2**, the equivalent floor space area of **570 m^2** considering that plants are cultivated on five-levels trays.

Interestingly, N and P were in higher concentration compared to the fertilizer recipes found in the literature (Orsini et al., 2020; Pennisi et al., 2019). Therefore, a lower quantity of treated urine had to be used to match either P or N concentration of commercial fertilizer recipe, causing the loss of more than 50% of the treated urine. However, when diluted with the effluent of treated greywater, urine could be safely discharged since COD concentration was way below the recommended EU standards. Pollutants concentration in treated greywater was consistently below the new standards proposed by the EU for treated greywater reuse in agriculture (Regulation EU, 2020). The greywater was treated on each building block through a vertical green wall of 70 m^2. The greywater coming from the dwellings was collected from each building into a collecting tank and then pumped into the green wall from the top. Treated greywater was then collected in tanks of 16 m^3 located at the bottom of each green wall. From there, an average of 10% of the treated greywater is used for irrigation and another 25% is recirculated within the building blocks for flushing and washing. The rest of the treated greywater could be safely discharged.

4. Conclusions and future development of the research

The wastewater treatment system coupled with two hydroponic production methods (the PFAL, and the iRTGs) proved to be efficient in removing pollutants in domestic wastewater, reaching optimal discharge standards. Furthermore, the decentralized wastewater treatment performed well in recovering almost all the nutrients and all the water required by the production systems. However, more applied research is needed to assess the content of harmful viruses and bacteria in the treated urine solution. Since heavy metals accumulation varies substantially among the different cultivar species, it is important to develop further research on heavy metal absorption of the selected crops when using them in BIA projects that intend to use urine and greywater as nutrient solution.

In addition, more research is currently being conducted on the economic feasibility of the system. The high energy inputs required by the MBBR reactor as well as the cost of machinery and installments may hinder the future development of wastewater recovery hydroponic systems on such small urban scales. However, the rising costs of fertilizers in Europe and in the US (Schnitkey et al., 2022) are calling for concrete actions to reduce the dependency from chemical fertilizers, opening the way for new solutions that can maximize the use of resources in food production. In this scenario, the results of this study are encouraging, demonstrating that it would be possible to use the liquid fraction of the wastewater streams as alternative nutrient solution for integrated hydroponic systems. Future research on real life prototypes is highly recommended to assess the quality of plants grown in similar BIA systems.

Declaration of Competing Interest

Authors declare no conflicts of interest.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.104449.

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Further reading

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