Journal of Cleaner Production 397 (2023) 136380

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Catalyzing the circular economy of critical resources in a national system: Case study on drivers, barriers, and actors in nutrient recycling

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ARTICLE INFO

Handling Editor: Mattias Lindahl

*Keywords:*
Nutrient recycling
Qualitative case study
Circular economy
Ecosystem approach
Critical resources
Driver and barrier approach

ABSTRACT

Cycling of nutrients, such as phosphorus (P) and nitrogen (N), is essential for all life: Nutrients are crucial for securing societies' food systems and valuable raw materials for industrial processes. Recycling nutrients from various side and waste streams instead of virgin nutrients has attracted considerable interest in the society, particularly as geopolitical and epidemic issues have caused many nations to reconsider how they ensure flows of critical resources by increasing the Circular Economy (CE) principles. This study examines what drivers and barriers catalyze nutrient circulation in national settings, requiring diverse actors to support intentional nutrient recycling. By taking multidisciplinary and ecosystem approaches, we examine diverse sociotechnical drivers and barriers and the actor ecosystem involved. We conduct an extensive qualitative case study on nutrient circulation (P and N) in a Finnish context, analyzing over 150 documents and interviewing over 20 diverse actors (from diverse companies through ministries to farmers) involved in nutrient recycling, from biowaste through agricultural biomasses and sludge from municipal wastewater treatment plants. Our study 1) generates an ecosystem actor map uncovering diverse actors enabling nutrient recycling in society; and 2) exposes technological, business, organizational, regulatory, linguistic, visual, and psychological drivers and barriers shaping nutrient circulation. It explains the sociotechnical preconditions for different actor/stakeholder groups to adopt and advocate circular economy (CE) principles for nutrient recycling, which are generalizable to other critical resources. The study contributes to CE research and advises practitioners by providing a comprehensive catalyst toolbox to advance nutrient circulation and facilitate its acceptability and diffusion.

## 1. Introduction

Due to planetary boundaries, society faces a growing need to increase circulation of important resources and materials, varying from nutrients through metals, plastics, and textiles, following the principles of the circular economy (CE) (Neves and Marques, 2022; Leipold and Petit-Boix, 2018). Increasing research has tracked the barriers which make the move towards the CE arduous (see, e.g., Ayati et al., 2022). Geopolitical conflicts and COVID-19 have broken industrial, country-crossing value chains and made many countries reconsider how they ensure circular flows of critical resources nationally, even when the business feasibility of such resource circulation is complex. As circulation of different resources and materials is often driven by technologies and innovation, much research is limited to examining circular technologies and their role in enabling circular resource flows or circular business models (Ma et al., 2018; Vaneeckhaute et al., 2017). Fewer studies consider how societal or cultural aspects drive – or inhibit – the CE in society (Ayati et al., 2022). Examining societal approaches is, however, crucial to our understanding of CE diffusion, as the move towards circularity requires individuals and organizations to adopt new practices and operations (Leipold and Petit-Boix, 2018; Ayati et al., 2022) and policymakers to make changes in social institutions such as norms and regulations (Ranta et al., 2018) that shape society-wide acceptance and implementation of circularity. Resource circulation happens between, and is supported by, diverse stakeholders, such as companies and public organizations, consumer-citizens, policymakers, and regulators, who can be jointly conceptualized as a CE ecosystem: diverse complementary actors who can reach a common, system-level

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https://doi.org/10.1016/j.jclepro.2023.136380
Received 8 November 2022; Received in revised form 17 January 2023; Accepted 7 February 2023
Available online 18 February 2023

goal of implementing CE principles such as recycling and reuse (Aarikka-Stenroos et al., 2021). Hence, the ecosystem approach is used as an analogy for biological ecosystems to refer to complex, multi-actor settings and has been increasingly applied to CE research (Whicher et al., 2018; Parida et al., 2019; Uusikartano et al., 2020). This approach allows us to build an understanding of all actors relevant to resource circulation and their distinctive, even conflicting, perspectives on such circulation in society.

The need to advance circularity in society has triggered multiple studies reviewing barriers and drivers to the CE in general (e.g., Kirchherr et al., 2018; Neves and Marques, 2022; Ayati et al., 2022) or in certain industries, such as construction and electronics (e.g., Rizos and Bryhn, 2022; Giorgi et al., 2022). In this paper we examine the drivers, barriers, and actor system for nutrient recycling, as nutrients are among the most critical resources for human life, and nutrient recycling and circulation has thus been on many governmental agendas and the focus of academic research (Hidalgo et al., 2021; Humalisto et al., 2021). To date, however, research has focused on technological advancements (e.g., Robles et al., 2020), the fertilizing properties of recycled nutrients (Czekala et al., 2020), and socio-ecological-technical approaches, especially regarding human excreta as the source of nutrients (der van der Kooij et al., 2020). It has not yet studied the business or more societal and cultural factors that drive or inhibit nutrient circulation. Nutrients circulate and flow inherently in the natural ecosystem; hence, the challenge for society is how individual and organizational actors can actively and intentionally recycle nutrients between food and industrial production and consumption in such a way that they generate economic and environmental benefits and do not end up as waste. Consequently, we explicitly differentiate between “nutrient cycling/circulation,” referring to a natural resource flow without human impact, and “nutrient recycling,” meaning that direct or indirect contribution by a human or organizational actor is needed to return nutrients to circulation through recycling activities.

To summarize, this research is motivated by identified research gaps concerning nutrient recycling, namely that neither the ecosystem of actors for nutrient recycling nor the sociotechnical aspects that enable them to actively or intentionally recycle nutrients in urban society has been studied. It is crucial to gain a full picture of the ecosystem of diverse human and organizational actors who can contribute to nutrient circulation via intentional recycling. Another critical issue is what encourages or hinders these actors to advance circulation via intentional recycling; thus, diverse drivers and barriers for nutrient recycling among the diverse actors must be investigated. Therefore, our multidisciplinary study examines the actors who can contribute to nutrient recycling in society and the diverse drivers and barriers that advance or complicate the attainment of this system-level goal. We pose two interlinked research questions.

- RQ1: Who are the diverse actors who can advance nutrient recycling at the national level, forming the needed actor ecosystem? To answer this question, we map the key actors in nutrient recycling in one regional system/context, namely Finland, Northern Europe.
- RQ2: What are the sociotechnical drivers and barriers for nutrient recycling among actors? To answer this question, we explore and conceptualize diverse socio-technological drivers and barriers, framed as catalysts, ranging from the technological, business, and regulatory aspects to the less studied sociocultural ones shaping nutrient recycling and its adoption and acceptance in society.

The empirical element of the study is an exploratory, extensive qualitative case study in Finland. Document analysis of over 150 data sources and structured interviewing of different actors generated a wide array of driving and barrier factors shaping the current state and future of sustainable nutrient recycling in a national setting. Abbreviations are explained in Appendix 1.

The study intends to contribute to CE research, particularly concerning CE barriers and drivers at a national level, adoption, and ecosystem research, by increasing understanding of CE ecosystems and the diverse actors who must be engaged to achieve system-level circularity goals, such as nutrient recycling in urban societies, and related catalyzing drivers and barriers. Our multidisciplinary research also contributes to nutrient recycling research as it answers the research call for societal perspectives on CE nutrient recycling.

## 2. Theoretical background

### 2.1. Nutrient recycling and circulation and its relevance to society

Nitrogen (N), phosphorous (P), and potassium are the main nutrients required to meet the needs of current food production. Traditional production of these nutrients faces challenges, since P and potassium are mined from finite sources and only available in certain regions of the world, and remaining reserves are lower-grade phosphate rocks (Dawson and Hilton, 2011). Nitrogen fertilizers, meanwhile, are produced from atmospheric nitrogen with the Haber–Bosch method, which consumes 1–2% of global fossil energy, resulting in 1.4% of global carbon dioxide emissions (Kyriakou et al., 2020). Production and inefficient use of fertilizers have resulted in surplus N and P in the environment, causing eutrophication and exceeding safe planetary boundaries (Steffen et al., 2015). However, these nutrients are widely available in different waste streams. For example, in Finland a total of 133.2 kt-N/a and 30.7 kt-P/a is available in different biomasses, of which 74.6 kt-N/a and 18.5 kt-P/a are found in manure, 12.8 kt-N/a and 2.6 kt-P/a in straw, and 8.3 kt-N/a and 4.5 kt-P/a in sewage sludge (Ministry of Economic Affairs and Employment, 2020). Thus, enabling nutrient recycling from existing streams to replace virgin nutrients would promote a circular nutrient economy. In 2018, global agriculture required the use of inorganic fertilizers, namely 39 Mt of potash ($K_2O$), 41 Mt of phosphate (as $P_2O_5$), and 109 Mt of N (Food and Agriculture Organization, 2021). Estimates suggest that in the EU, 17–31% of the P could be replaced by 2030 with recycled nutrients in the form of struvite, biochar, or incineration ashes derived from manure, municipal wastewater, and sludges (Huygens et al., 2019). Nutrients are also present in natural water bodies, causing eutrophication. This study, however, focuses on more concentrated nutrient streams, the treatment of which is clearly a responsibility of certain actor(s).

When nutrients are used in agriculture, they may end up in crop waste, manure, or food ingredients. After food is consumed, nutrients are diverted to municipal wastewater and biowaste, and, although some are recycled back to agriculture, recycling is not always efficient. Spreading manure on fields as such can result in nutrient losses causing eutrophication (Corbala-Robles et al., 2018), and, as nutrient-rich streams and nutrient-deficient agricultural lands are often distant from each other, processing of nutrient-rich biomasses would be required to enable the transportation of nutrients between them (Parchomenko and Borsky, 2018). The organic contaminants, heavy metals, etc., in the sewage sludge hinder the utilization of nutrients, for example due to legislative restrictions (Christodoulou and Stamatelatou, 2016; Seleiman et al., 2020). Wastewater treatment plants (WWTP) principally aim to remove nutrients from wastewater and prevent nutrient run-offs to the environment; thus, much work remains to convert traditional WWTP into resource recovery factories (Coats and Wilson, 2017).

To enable nutrient recycling, nutrient-rich streams often require processing. Biomasses or waste streams that contain organics, such as manure, crops, biowaste or sewage sludge, can be processed in anaerobic digestion. During anaerobic digestion part of the organic fraction is converted to biogas that can be used as an energy source, e.g., for production of heat and electricity or upgraded into vehicle fuel, and the remaining digested fraction, i.e., digestate, contains most of the nutrients (Vaneeckhaute et al., 2018; Ma et al., 2018). Digestate is already a stable product that could be used as an organic-mineral fertilizer (Vaneeckhaute et al., 2013; Tampio et al., 2016) or the digestate can be further processed to decrease the volumes (and thus transportation distances) and/or to concentrate the nutrient and carbon products (Ma et al., 2018). Upon processing, digestate is first mechanically separated into solid and liquid fractions. From the liquid fraction, P and/or N can be recovered, e.g., via P precipitation as struvite or calcium phosphate, ion exchange and adsorption, and N can be recovered, e.g., via ammonia stripping, acidic air scrubbing, or membrane filtration (Vaneeckhaute et al., 2017; Shi et al., 2018). The solid fraction of the digestate can be treated via composting or with thermal treatments, such as incineration, pyrolysis, and hydrothermal carbonization (Shi et al., 2018; Barampouti et al., 2020). The end-products of liquid fraction treatment as well as the biochar and hydrochar from pyrolysis and hydrothermal carbonization, respectively, can often be used as such as nutrient resources, while from ashes of incineration P could be further recovered with different leaching methods (Vaneeckhaute et al., 2017; Barampouti et al., 2020).

### 2.2. Extant knowledge on drivers and barriers for nutrient recycling in society

Next, we discuss the current understanding of barriers and drivers shaping nutrient recycling. Research on barriers and drivers for CE – in general and within certain industrial sectors – suggests barriers can be categorized into technological (available technologies), economic and market-related (economic viability of circular business models), and regulatory (policies, incentives, and consensus). Although some cultural and societal factors have been noted, such as consumers' unwillingness to adopt circular practices or lack of education (Kirchherr et al., 2018; Ayati et al., 2022), studies more often address barriers than drivers.

Previous studies focusing nutrient recycling have also indicated some policy and regulative drivers and barriers, such as political continuity (Angouria-Tsorochidou et al., 2021) green deals and the inclusion of P in the EU critical materials list (de Boer et al., 2018). Regulatory barriers include the arduousness of navigating the jungle of EU countries' differing legislation concerning use of treated sewage sludge in agriculture (van der Kooij et al., 2020) and revising and implementing legislation concerning fertilizers and end-of-waste status. From an economic perspective, studies acknowledge that the market still suffers from long-distance biomass transportation and logistical unprofitability (de Boer et al., 2018; Vaneeckhaute et al., 2018), conservative attitudes, low prices of virgin fertilizers, and the uncertainty of investment returns (de Boer et al., 2018).

Studies indicate that urban nutrient cycles still face ideological, institutional, and knowledge barriers (Kanter et al., 2020), collective vision and integrated approaches are lacking (de Boer et al., 2018), accountability boundaries are unclear (Angouria-Tsorochidou et al., 2021; Vaneeckhaute et al., 2018), and mindsets must be altered concerning recycled nutrient streams and their heavy metal- and pathogen-related safety and health issues at both individual and EU level (de Boer et al. 2018, 2018van der Kooij et al., 2020; Vaneeckhaute et al., 2018). Additionally, studies state the importance of an ecological perspective to determine the efficiency of plant–soil interactions in an agro-food system that utilizes recycled nutrients (van der Kooij et al., 2020), observing that incorporating socio-ecological factors into studies concerning urban nutrient flows is necessary to improve sustainable nutrient management (Metson et al., 2015). Most studies focus on a single nutrient flow or specific technological process and observe it through the lenses of different disciplines and in varying geographical contexts.

These earlier studies above build initial understanding on drivers and barriers for urban nutrient recycling, and relevant actors, and this study aims to develop this understanding via qualitative case study that is explained next.

## 3. Methodology

### 3.1. Research design and case setting

To develop a theoretical understanding of the actors who can contribute to nutrient recycling in a society and related drivers and barriers, we selected an extensive qualitative single case-study research strategy, as this enables analysis of complex phenomena that are not easily separable from their context (Yin, 1994). The case unit is an extensive multi-actor ecosystem comprising diverse stakeholder actors who can advance or hinder nutrient recycling within a single national system, some of whom also operate globally. The case captures various actor types, numerous organizations, and both ongoing collaborative actions and political determination to promote nutrient recycling.

As context, manure and other biomasses from agriculture contain the most recyclable P and N of Finland's nutrient-rich streams: 75% of Finland's recyclable P originates from manure (Marttinen et al., 2018) in contrast to 70% in the EU (Buckwell and Nadeu, 2016). Other nutrient-rich streams include biowaste and municipal and industrial wastewater sludge. In Finland, manure and other nutrient-rich streams in agriculture are produced in different regions than those where the nutrients are required, resulting in a regional nutrient imbalance (Marttinen et al., 2018). Hence, intentional action is required to recycle nutrients through collection and redistribution. Nutrient recycling is on the Finnish government's agenda and of interest throughout the EU, where the new Fertilizing Products Regulation (Regulation (EU) 2019/1009) is being implemented. Although this regulation is implemented in Finland, various regional regulations and interpretations also affect nutrient recycling.

The selected case is also expected to be generalizable: Globally, it is necessary to enhance the circulation of nutrients and decrease the environmental impact of nutrient use (Hidalgo et al., 2021). The boundaries of the observed ecosystem were set to the circulation of P and N in an anthropocentric setting within which nutrients from various side and waste streams are recycled via multiple recycling processes, and the recycled nutrients are used as extensively as possible as substitutes for virgin nutrients.

### 3.2. Data collection and analysis

Data collection was designed to capture the multiple perspectives of involved ecosystem actors (companies, governmental bodies/ministries, farmers, municipal actors, research institutes, non-profit organizations) and their views on drivers and barriers for nutrient recycling. Data were gathered from multiple sources, primarily via interviewing (semi-structured interviews) and document sourcing (see Table 1), between August 2020 and February 2022. Interviewees were key experts and managers or other key actors from the organizations in the ecosystem. The primary data sources include 24 interviews and observation; secondary data sources were research publications, media data, minutes, and other documents (see Table 1).

Interviews followed an interview guide addressing themes including background information and diverse driver/barrier types (technology, business, management, regulation, visualization, language, and psychology). Interviews typically lasted 80 min and were recorded and transcribed. The interview guide was sent to interviewees before the interview, and interviewees were able to check and validate their interviews afterwards. The list of interviewees in Appendix 2 gives information on their positions, roles, and operating fields in the ecosystem.

In the analysis phase, we aligned existing research knowledge on circular ecosystems, drivers, barriers, and nutrient recycling with empirical findings from our extensive case study, thus following the logic of abductive reasoning, which is particularly useful for theory development (see Reichertz, 2004). Regarding RQ1, we generated an overview of the ecosystem actors and structure, identifying relevant

**Table 1**
Overview of data sources in the case.

| Data type | Data: amount and description | Role in analysis and research |
|---|---|---|
| Primary data | | |
| Interviews with key actors representing complementary roles in the ecosystem (farmers, policymakers, etc.) | Interviews (n = 24); semi-structured interviewing, with an interview guide | Mapping ecosystem actors (RQ1); examining drivers & barriers (RQ2) |
| Observation, ethnographic follow-up | Workshops (n = 3) involving diverse stakeholder actors<br>Seminar or webinar presentations, e.g. *RaKiKy - Competitiveness from nutrient recycling, November 2020* (N = 12) | Interviewee selection (RQ1); examining drivers & barriers (RQ2) |
| Secondary data | | |
| Media data, Companies' and organizations' documents | Company/organization websites (n = 65)<br>Brochures (n = 9) | Theoretical background, interviewee selection (RQ1) |
| Research reports and publications | Research and project reports (n = 13) Journal articles (n = 41)<br>Theses (n = 2)<br>Briefings, presentations, press releases, e.g., *Operational programme of nutrient recycling 2019–2030* (n = 11) | Theoretical background, interviewee selection (RQ1), and drivers & barriers (RQ2) |
| Other | Acts and directives, e.g., *The EU Fertilizing Products Regulation* (n = 2) | Regulatory drivers/ barriers for nutrient circulation and recycling (RQ1 and RQ2) |

actors and their roles to enable detailed analysis of the composition of the ecosystem for nutrient recycling. Regarding RQ2, we applied thematic analysis to examine the catalysts: First, we examined the data generated by each interview; then, we compared data across interviews and other data sources and compiled concurring themes and similarities. By identifying and analyzing critical drivers and barriers we developed an extensive spectrum of catalysts that can drive nutrient recycling within the ecosystem. Multiple tools and tactics enhanced the analysis: Kumu software (a data visualization tool for creating interactive relationship maps), in particular, was used to analyze ecosystem actors and structure. The quality of our results was ensured by different modes of triangulation (Flick, 2004), while collecting different types of data (interviews, observation, reports, etc.) throughout the process and from different ecosystem actor sources increased data triangulation. Moreover, as three researchers from different disciplines contributed equally throughout the research process, we also implemented researcher triangulation: researchers discussed analysis procedures and compared the actual results (e.g. actor types; barrier/driver categories) jointly to ensure trustworthiness of research results.

## 4. Results

### 4.1. CE ecosystem actors contributing to nutrient recycling in urban society and their diverse perspectives

As our analysis uncovers, the actor ecosystem for nutrient recycling involves multiple companies and different industries as very diverse material streams can be used in nutrient-recycling processes. This study focused on ecosystem actors related to three relevant nutrient streams: municipal biowaste, municipal wastewater, and agricultural streams. Fig. 1 visualizes the results of our ecosystem mapping by displaying the main actors able to contribute to nutrient recycling at national level.

Fig. 1 displays the diversity of the ecosystem actors needed for nutrient recycling: not only businesses and policymakers, but actors from multiple business sectors. Farmers both utilize recycled fertilizers for plant farming and handle agricultural streams, such as manure and excess plant biomass, and companies are from diverse industries. Food industry actors include food companies, butcheries, grain mills, and animal feed producers, who process farmed goods into food products and direct excess side streams to recycling processes. In forestry and the forest industry, fertilizers can be used by timber growers and nutrients in the wastewater treatment processes of pulp and paper manufacturers. Municipal WWTPs and waste management companies process large quantities of municipal nutrient-rich streams such as municipal sewage sludge and biowaste, for example via biogas process or composting. In addition to producing energy, biogas companies play an important role in recycled nutrient production, as the digestate generated can be used as recycled fertilizer. Furthermore, virgin and recycled fertilizer manufacturers and industrial chemical manufacturers refine recycled nutrients or provide necessary chemicals for the recycling processes.

Universities and research institutes also contribute via research and technology development, for example in nutrient-recycling processing technologies and safety assessments. Authorities, such as regulators and ministries, contribute via policymaking that encourages, pushes, or enables other actors to adopt and implement the safe and effective circulation of nutrients. They regulate, create norms, and resource nutrient recycling-related actions in society. Associations, unions, and central, regional development, and non-governmental organizations promote the interests of their members, create new business opportunities within national regions, demonstrate and communicate latest research to their target groups, and publicize the importance of environmental sustainability regarding nutrient circulation. The media convey information and thus raise awareness about nutrient recycling-related matters.

These actors' involvement and motivation to contribute to nutrient recycling varied: Environmental sustainability was the most addressed motive in interviews, in terms of planetary boundaries, criticality of P resources, energy intensity of N capture, eutrophicated water bodies, biodiversity loss, and maintaining soil quality by carbon farming. Food safety and the integrity of the global food system were also highlighted. At national level, actors wanted to address virgin nutrient imports and cited nutrient self-sufficiency as a reason to support nutrient recycling. Actors also mentioned the geographical imbalances between areas with nutrient-rich streams and those with nutrient deficiency and that closing such loops in a cost-efficient manner was crucial. From both general and national perspectives, interviewees highlighted the general CE ideology and need to reduce excess use of resources. Business opportunities around CE and nutrient recycling were also mentioned as motives: Interviewees highlighted technological knowhow in Finland and the chance to lead the way globally in the sustainable circulation of society's nutrient streams.

### 4.2. Sociotechnical drivers and barriers for nutrient recycling perceived by actors

Seven sociotechnical driver and barrier types were identified and categorized from our exploratory analysis: *technological*, *business*, *organizational*, *regulatory*, *linguistic*, *visual,* and *psychological*, as discussed in more detail below and summarized in Fig. 2.

#### 4.2.1. Technological drivers and barriers for nutrient recycling

The main technological drivers for nutrient recycling were processing technologies, such as *nutrient recovery and digestate post-processing technologies*, which enable efficient recovery of nutrients and their concentration. For example, most of the Finnish wastewater treatment plants currently use ferric salts to precipitate P, which, however, does not easily dissolve and be readily available for plants. Thus, better P recovery methods from wastewater treatment plants are required. Furthermore, although N is more readily soluble in many waste streams,

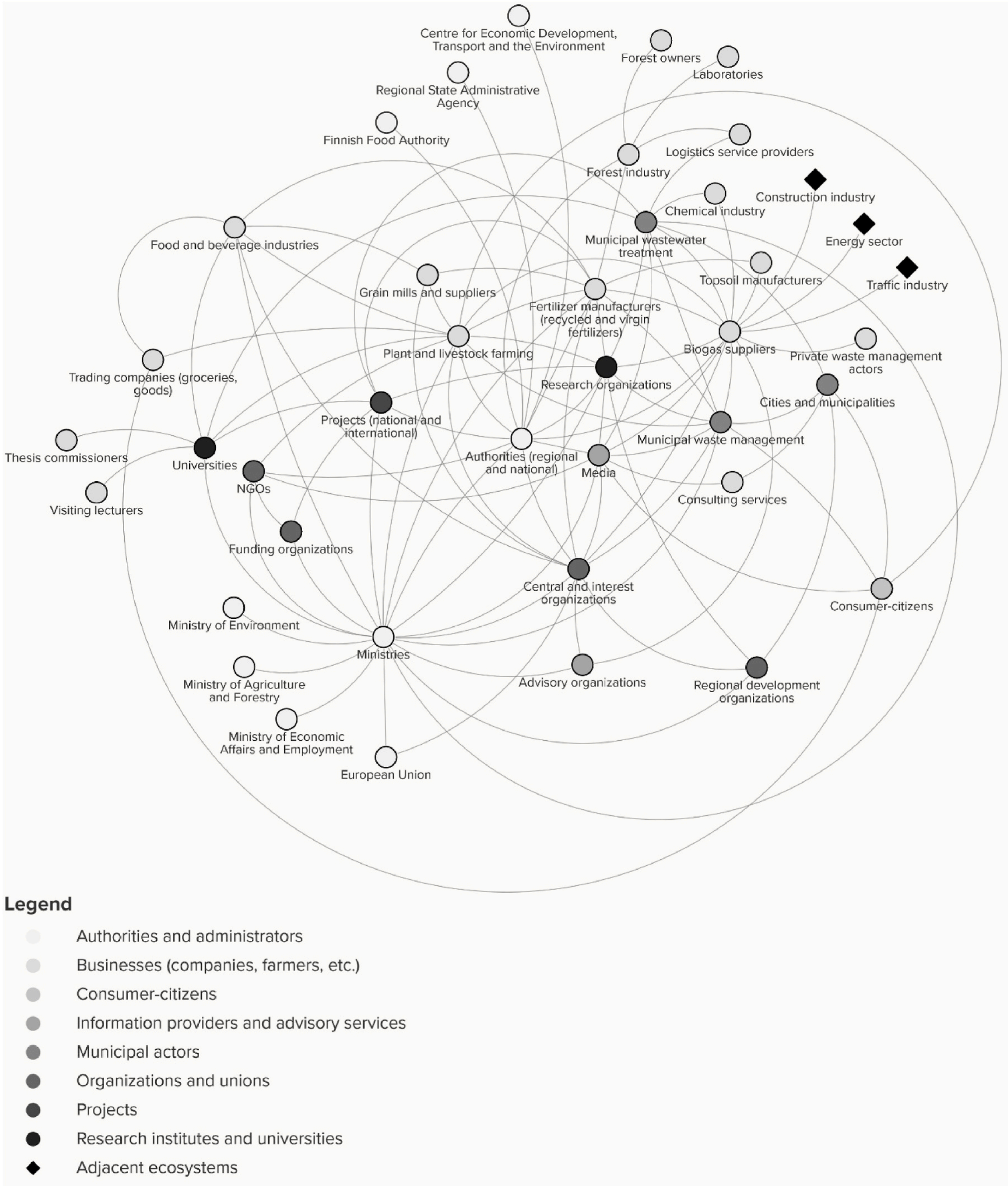


**Fig. 1.** The composition of an actor ecosystem for nutrient recycling in Finland.

it evaporates easily when in touch with air or if the temperature is too high and thus, more efficient technologies for N recovery are also needed. Another main technological driver is *biogas technology*, which results in nutrient-rich digestate, an inseparable part of the biogas process. Therefore, any up-scaling and developments in biogas production as believed to benefit the society's nutrient cycles as well. However, post-processing technologies were particularly mentioned as enablers of biogas technologies to develop an advanced and market-worthy recycled nutrient product: One fertilizer regulation authority noted that "*looking back,*" prevalent fertilizer production technologies had been "*mostly minimum-level … and arisen from the needs of waste management … they've been developed out of necessity to meet authorities' requirements, rather than having been developed from the point of view of a functioning and safe product.*" Technologies considered to contribute to the processing of digestate by the interviewees included pyrolysis, high temperature carbonization, stripping to produce ammonia water, struvite precipitation for P recovery, and membrane stripping for N recovery. In addition to technological solutions, the homogeneity of the feed was considered crucial, as it improves the predictability and quality of the recycled nutrient product. One interviewee mentioned that the quality of biomass streams from multiple farms varies more than that of industrial side or waste streams, which are more homogeneous.

*Tech-based process and product development* supporting biomass processing in both industrial processes and households were mentioned. An interviewed waste-management actor mentioned that new technologies are required to refine biowaste – a nutrient-rich stream – alongside with

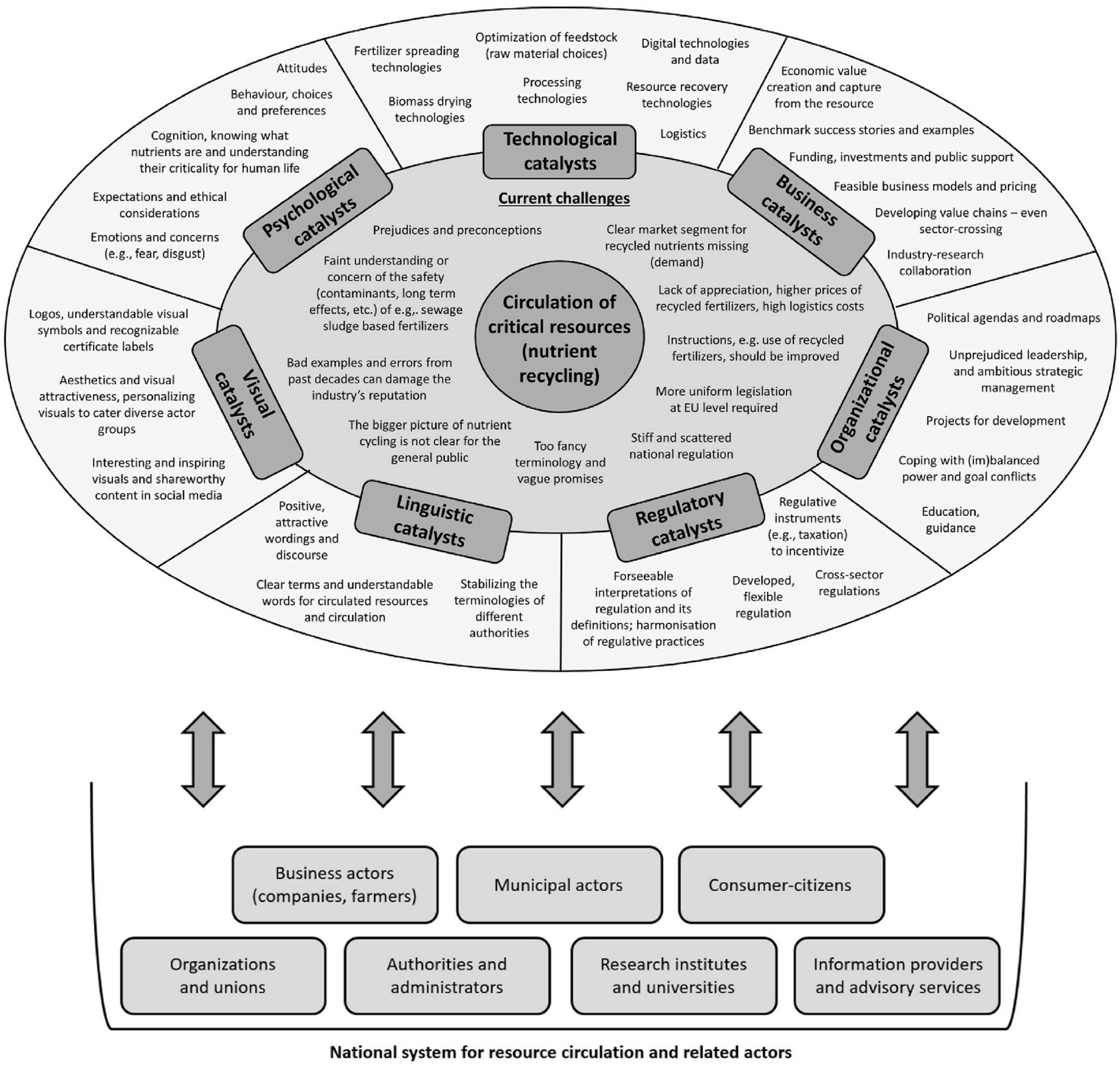


**Fig. 2.** Conceptual framework: Sociotechnical catalysts shaping circulation in the actor system, here nutrient recycling in a national setting.

the conventional sieving to remove visible impurities (plastics, glass, metals, etc.) more efficiently. A municipal waste management company also highlighted a technological problem regarding biowaste bags, stating that "*bio-based*" does not necessarily equal "*biodegradable*": therefore, development of biowaste bags that biodegrade quickly and efficiently, including in the anaerobic conditions that prevail in biogas processes, would ease nutrient recycling.

Interviewees suggested developing *technologies for drying and condensing biomasses* was a crucial technology driver, as the high-water content of biomasses increases their mass and thus *logistical costs*. It was suggested that the high-water content of many recycled fertilizers, compared to virgin fertilizers that are traditionally in the form of solid grain, may also complicate the mechanical use of fertilizers in agriculture. Thermal drying methods, such as pyrolysis and wet pyrolysis, and further drying were mentioned by the interviewees as technologies that can yield more easily applicable grain-form fertilizers. However, drying biomasses is highly energy-intensive; thus, the cost-efficiency of the process is not yet considered sufficient by the interviewee. A biogas company interviewee suggested arranging the drying process in symbiosis with other heat-releasing industrial processes. *New digital solutions* were also suggested as means to tackle prevailing inefficiencies in technological refining and delivery chains, i.e., logistics. A suggestion was made for a digital marketplace, to sell the digestates from biogas processes to end users, could be used to optimize logistics.

Technology drivers also include better technologies and machinery for agriculture, for example to *spread* recycled fertilizers on fields. Developing granular-form recycled fertilizers that could be spread in a cost-efficient way with existing equipment was highlighted, but some agricultural interviewees also suggested that agricultural machinery manufacturers could develop new types of fertilizer-spreading equipment to cater for different recycled fertilizers.

Multiple actors also highlighted that tech-based yet more *holistic approaches* could drive diverse actors to recycle nutrients. One suggestion was that *carbon farming* could improve soil health and quality and benefit nutrient uptake. Furthermore, to guarantee sufficient nutrient uptake, it is crucial to find the right combination of different recycled fertilizer types with different soil conditions, farming equipment and growing cycles. However, such approaches require more motivation and time from farmers than using artificial fertilizers. *Safety concerns* similarly require science- and tech-based approaches: Utilizing nutrients originating from municipal WWTP as fertilizer has been universally controversial due to safety concerns and insufficient data about possible contaminants and residues. Thus, many interviewees agreed that safety issues required further technological research, particularly on the long-term effects of potential contaminants on soil and people.

#### 4.2.2. Business drivers and barriers

Business-related drivers and barriers for nutrient recycling focused on funding *directed to nutrient-recycling projects*, *collaborative product development*, feasible *business models*, and, in particular, *prevalent prices of recycled fertilizers*. To make business from nutrient recycling, a clear distinction between recycled nutrients, recycled raw material, and recycled fertilizers is required: When recycled fertilizers exist as a product category, their commercialization and sale is easier. One critical business barrier was a lack of appreciation for recycled fertilizers: "*Some understand that when the product is safe to use and produces crops, they are also expected to pay for it, but there are also those who still perceive the digestate as agricultural waste that just happens to have gone through a biogas process and are reluctant to use it – and if there is a price on it, they definitely will not use it,*" one biogas producer explained. The lower cost of virgin fertilizers (as recycled ones incur e.g., higher logistics costs, particularly in Finland, where distances are long) was cited as a dominant cause of recycled products' failure to attract customers, mainly farmers. Funding *and public* support for nutrient recycling and carbon farming were also named as important drivers. In Finland, focused external funding was provided by the Ministry of Environment, Ministry of Agriculture and Forestry, Ministry of Economic Affairs and Employment, Business Finland, and Sitra, enabling multiple nutrient-recycling projects and investments and bringing much-needed visibility to small enterprises. One fertilizer manufacturer had noticed a gradual, increased recognition of the utilization of industrial side streams in agriculture and industrial actors' increased willingness to undertake CE-related investments based on trends that might become profitable within 10 years or so. One driver for economic value creation was *sharing best practices through success stories,* for example on agrological symbioses, where nutrients mainly circulate in smaller cycles, in a cost-efficient and mutually beneficial way.

Relevant *cross-sector and industry-research collaboration* was found to drive market and business development of nutrient recycling among farmers, companies, universities, and research institutes. For example, actors have jointly created a quality certificate system for recycled fertilizers (Laatulannoite[1] in Finland) to ensure and demonstrate their quality and thus strengthen their commercial value and business model. Business-oriented collaboration enabled different technology providers to combine their expertise to create commercially strong new solutions. Correspondingly, actors who develop and produce recycled fertilizers could join forces to develop fertilizer quality even further. Universities contributed by developing research-based knowledge on nutrient recycling, including CE education their curricula, and providing competences and knowledge for companies and indirectly strengthening their businesses through industry–university collaboration. Relatedly, integration of *diverse competences* was called for to drive businesses for nutrients, although, interestingly, the *diversity of actors for nutrient recycling* was also a barrier to developing business. Industrial and agricultural actors rarely meet to co-create understanding of how to recycle nutrients and produce new types of recycled fertilizers in a commercially feasible way. For example, biogas treatment plants may lack the knowhow of farming conditions and plants' nutrient requirements, whereas farmers may lack awareness of industrial processes and utilizable side streams – an equation that requires extensive cross-sector knowhow from recycled fertilizer manufacturers.

#### 4.2.3. Organizational drivers and barriers

Regarding organizational drivers and barriers, many actors highlighted the need for *leadership* and *ambitious strategic management* acknowledging the CE and circulation of critical resources. *Political agendas and roadmaps* (e.g., the EU Green Deal strategic program[2] and Finnish government's CE agenda[3]) were also mentioned as critical organizational drivers. Further, informants wanted more focus on persistently *implementing* the visionary goals, agendas, and strategies, as observed by a ministry representative. They argued that the lead could be taken by public municipality-owned actors, who may be able to set more ambitious climate goals than companies in the name of public responsibility and even prioritize such goals over profits, whereas companies may be unable to take risks and ground their business models fully around nutrient recycling.

Organizing for nutrient recycling was often complicated by *unbalanced power*: For example, the studied actor ecosystem comprised many enthusiastic, small companies with world-saving ideologies and limited resources as well as large companies with significant power and expertise, but who are more careful with their investments and statements. Furthermore, different *conflicting interests and goals* were seen as barriers. For example, bringing a new circular business model to rural areas of Finland might provoke negative comments and discouraging feedback. Additionally, old habits die hard when it comes to utilizing biomasses: Many actors were seen as still failing to grasp the bigger picture of nutrient recycling and its opportunities over time, possibly resulting in many potentially useful side streams being incinerated as waste.

Competences and education seemed to drive recycling: Focused competence in CE or nutrient recycling within companies was mentioned as an important driver, requiring organizing, such as having a specific CE unit or recruiting a dedicated expert. *Education on CE* and nutrient recycling, among other sustainability aspects, was another important driver in catalyzing the circulation of critical resources. However, as universities have limited resources, nutrient recycling might lack the necessary cross-disciplinary attention, for example in agricultural or environmental studies. A ministry representative also remarked that circular, systemic thinking should be better incorporated in all university studies: It is not enough that only some disciplines and education fields acknowledge the criticality of nutrient recycling and needed competences; rather, understanding must crosscut disciplines.

Organizations' *external communication and guidance* were considered powerful drivers for nutrient recycling. Transparency was relevant, especially in global communication, as countries can differ greatly in terms of culture, legislation, and operating principles. Interviewees pointed out that opinions, terms, and attitudes related to nutrient recycling vary greatly among international business partners, even within Europe. Therefore, open communication on circularity goals, achievements, and even failures, was underlined, as was the importance of communicating and sharing "best practices" and practical examples. Clear, *practical guidance and instructions on how to implement nutrient recycling* were also considered important: Instructions for the use of recycled fertilizers have sometimes been considered unclear. It is crucial that farmers can try out new research findings in practice on their own farms. *"Getting farmers involved, doing things on fields in practice, and generally approaching topics and solving problems from the farmer's own point of view is the way to share information,"* one fertilizer manufacturer noted; *"if you go through the same things from the perspective of somebody's own plot of land, those things are more easily put into action."*

The *dissemination of existing, recent research or practice-based knowledge* was also deemed crucial: Our Finnish case showed that many projects had generated important insights on nutrient recycling, but they did not always seem to reach regulators, authorities, or companies. Interviewees pointed out that fertilizer manufacturers and food companies, for example, have a great opportunity and responsibility to actively communicate recent research and sustainable methods of farming to their agricultural stakeholders. The ministry representative

[1] Laatulannoite: The Finnish Quality Assurance Scheme for recycled fertilizers, "Laatulannoite." Certification rules available in Finnish in Laatukäsikirja: Kansallinen laatujärjestelmä kierrätyslannoitevalmisteille (Quality Handbook).

[2] European Commission: The European Green Deal.

[3] The Finnish Government: Government Resolution on the Strategic Programme for Circular Economy.

also noted that actors with the same cause and operating field organizing themselves under the same organization or union may serve as an amplifier and enable better communication. Indeed, in Finland, separate biomass circulation and biogas unions have amalgamated into one larger union, underlining the importance of organizing for knowledge sharing within and across industries as a driver.

#### 4.2.4. Regulatory drivers and barriers

As expected, regulatory drivers and barriers crucially shaped the involved actors' participation in nutrient recycling. *EU-level obligations for waste treatment* impact and steer nutrient recycling planning and scaling within EU member countries. In particular, the recently updated (in 2022) *EU fertilizer legislation*[4] was mentioned as an important driver, as it now acknowledges organic and side stream fertilizers and soil amendment products. The updates will enable *CE markings* for such fertilizers, providing easier mobility and operations across national borders. However, it was argued that *regulatory differences or interpretations within different countries* can complicate product sales. Therefore, a more uniform interpretation of nutrient recycling-related matters at EU level would bring more stability and make investments and expansions smoother. On the other hand, there are concerns that common EU-level obligations may prevent the safe circulation of certain nutrients: For example, if a regulation to incinerate municipal sewage sludge in all EU member countries were set, Finland would not be able to use its full technological potential for nutrient recovery.

Interpretations of regulations can also serve as both driver and barrier: For example, whereas current legislation enables the spreading of organic fertilizers (e.g., processed sewage sludge-based fertilizers) on fields in Finland, it does not allow them to be used as a forest fertilizer. As one interviewee pointed out, one regulatory quirk may seem trivial, but a series of such drawbacks can cause major challenges, as companies cannot anticipate interpretations that become business risks for them and their nutrient-based business development. Consequently, actors expressed the need to develop national regulations and inclusive dialogue between different actor groups during regulatory planning: "*When legislation is developed and updated, it is crucial to have an active dialogue with the industry's actors, so that the legislation will be both appropriate and up-to-date, and that it specifically* supports *the activities and does not set unnecessary boundaries to CE actors,*" one municipal wastewater treatment representative emphasized, adding, "*this is a quickly evolving industry, which is why open conversation between different actors is needed.*"

*Regulatory definitions of waste* (i.e., what is waste and what is a side stream) have, according to interviewees, to date been favorable for nutrient recycling in Finland. However, many interviewees agreed that the national regulatory environment is scattered and that the myriad legislative rules that affect operations, such as *end-of-waste legislation*[5] *and REACH chemical legislation*,[6] require thorough familiarization and understanding. For example, receiving side streams from industries and selling recycled nutrient products to end users entail operating under multiple different ministries and authorities, creating a fragmented operating environment in regulatory terms.

The current product *safety and environmental regulations* were also highlighted. For example, the nitrate legislation and P limits in environmental permits limit the field use of fertilizers, which was agreed to be important from an environmental perspective. The priority should always be to treat waste and hazardous contaminants safely, and nutrient recycling should not be advanced at the expense of the environment and people. However, the importance of re-evaluating the risks and finding new solutions to mitigate them was highlighted. For example, wastewater generated near central hospitals tends to have high concentrations of medical drug residues; thus, decentralized treatment and preventing it from mixing with other wastewater should be considered.

*Harmonization of practices and regulative communication* and simple, coherent guidelines concerning, *inter alia*, contaminants and hazardous substances are desperately needed when waste streams are converted into commercial products. Our findings also highlighted the increasing importance of developing feasible regulation by acknowledging adjacent industrial ecosystems where resource flows cut across conventional industry sectors. For example, regulations concerning the traffic industry will likely affect the biogas sector as biomethane is used as fuel, which, in turn, links to the recycling of nutrients. Some interviewees also felt that the cross-sector regulations affecting nutrient recycling do not fully reflect Finland's ambitious nutrient-recycling goals. Measuring of carbon sequestration or support systems for carbon trading in agriculture were suggested as possible future drivers for more efficient nutrient recycling.

Many of these regulatory drivers and barriers interlink with business drivers and barriers. Regulatory instruments were considered effective ways to initiate investments and new business: One interviewee pointed out that an obligation to distribute biogas could provide a well-needed nudge for nutrient recycling. However, whereas some interviewees favored obligatory nutrient recycling, such as in the form of a mixing obligation (a certain percentage of recycled content mixed with virgin content), others questioned the use of producing circular products simply to meet regulatory demands if they were not attractive to customers due to functional insufficiencies or uncompetitive prices. On the other hand, it was suggested that the current low prices of virgin nutrient products should be re-evaluated according to their environmental impact or, correspondingly, that more support or tax reliefs should be assigned to recycled nutrient products.

#### 4.2.5. Linguistic and communicational drivers and barriers

Regarding sociocultural drivers, *clear words and understandable terminology* were considered important, underlining the relevance of linguistic drivers. The need to clarify and unify certain terms between and among different actor groups was highlighted, both nationally and at EU level. For example, clear differentiation between the terms *recycled nutrient*, *recycled raw material*, and *recycled fertilizer* and *product*, *by-product,* and *waste* was considered crucial. One interviewed authority representative also pointed out the differences in legislative terminologies between different operating fields. Thus, it is important to address different material streams carefully, for example in environmental permits, as the processes to remove the waste status of materials that were once claimed as waste can be lengthy.

*Attractive words and positive connotations* were also mentioned as drivers, and multiple interviewees highlighted the need for *positive word choices and discourses*. Appreciative wordings in general discussion concerning, for example, industrial side streams' value and beneficial properties were not only considered to increase valuation and interest among end users, but also to drive the industry itself to improve the quality of their side streams. Certain nutrient recycling-related words were also experienced as drivers and barriers. For example, it was suggested that the word "*biogas*" created positive mental images due to its media coverage in relation to alternative fuels, among other things.

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[4] EUR-Lex: Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilizing products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 (Text with EEA relevance). Document 32019R1009.

[5] EUR-Lex: Consolidated text: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance). Document 02008L0098-20180705.

[6] EUR-Lex: Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. Document 32006R1907.

Correspondingly, the word "*recycled*", as in "recycled nutrients," was regarded as having a positive ring due to environmentally conscious success stories from other fields of industry. On the other hand, it was suggested that nutrient recycling-related words such as "*digested sludge*", "*urea,*" and "*feces*" created negative emotions, as did word combinations such as "*wastewater sludge-based fertilizers and food production.*" However, it was pointed out that the mental images conjured up by certain words evolve over time: Decades ago, the word "*compost*" equaled "*a dump,*" whereas now it has a positive ring. Thus, when proposed and advertised carefully, even initially off-putting words can be made attractive.

Understandability was found to be another driver: Nutrient circulation in the food system and in society is complex to explain to a consumer-citizen, and there was a clear consensus that many people find nutrient cycling and recycling unclear. Some interviewees also pointed out that news and articles about nutrient recycling often tell the story from one actor group's point of view, leaving the bigger picture of society's nutrient cycling fuzzy. However, due to the complexity of nutrient cycles and a multitude of different related material streams, condensing the information into a clear package and showcasing all its linkages, especially in mainstream media, was agreed to be challenging: "*It is always a challenge, trying to handle the topic in an article in the most unbiased, interesting, reliable, and objective way as possible, and trying to include all the possible actors and all the processing technologies and all the exceptions to exceptions,*" the professional magazine representative said, concluding that "*One must just go for the policy that in the long run, and in the bigger picture, in a continuum of multiple issues, the entity should become addressed in a sufficiently representative manner.*" Media discussion of nutrient recycling, in particular, was identified as either a driver or an inhibitor: Most interviewees felt that media coverage about nutrient recycling in Finland has been mostly positive and clear and even observed that appreciation of farmers and Finnish food production in different media increased during COVID-19. However, some interviewees thought that waste and wastewater handling-related matters – despite their crucial role in society's nutrient cycling – tend to make the news only on negative occasions and would benefit from positive headlines and prioritization of the most important issues.

#### *4.2.6. Visual drivers and barriers*

Regarding visual drivers and barriers, among the most important ones were visual symbols, or logos, increasing awareness and noticeability. Memorable certificate labels were mentioned as positive drivers in acceptance of recycled nutrient products. Some interviewees noted that regulatory acceptance alone does not always convince users that a product is good; for example, the recent Finnish "Laatulannoite" quality certification symbol was perceived to increase awareness of recycled fertilizers, but new certificates and symbols can also be lost among the abundance already in existence: "*Consumers need to be so thoroughly conscious about everything if they wish to interpret the symbols. I think it should be a basis for everything, that if you buy a product from a store, you can already be sure that it has been produced sustainably,*" one interviewee remarked.

Multiple interviewees agreed that pictures and art can be powerful drivers for action and highlighted the importance of approaching change with encouraging visuals. However, the importance of choosing pictures carefully for each separate actor group within the ecosystem, for example during campaign and product advert planning, was acknowledged. Furthermore, visual influencing impacts different people differently within the same actor group: For example, persons living in urban versus rural areas might be affected by highly different visual messages. It was also acknowledged that in certain cases negative visuals have their time and place. For example, brutal pictures of the state of the environment, such as eutrophicated algae reefs, can drive certain consumers' interest towards more sustainable choices. On the other hand, incriminating specific actor groups should be avoided. For example, visuals related to nutrient loading-imposed eutrophication often illustrate a rural scene with fields or cattle sheds, which may leave the reader with the unrealistic perception that agriculture is the only source of emissions.

*Aesthetics and visual attractiveness* also play an important catalyzing role: In general, nutrient recycling in society was considered a highly unaesthetic topic and aesthetics – or lack of them – clearly have a communicational impact on the consumers. For example, visual messaging that grocery stores' delivery trucks are running on biowaste in the form of biogas is an efficient way to empower consumer-citizens towards more active biowaste sorting. Some interviewees remarked that even cleanliness can be considered a driver: Clean processing or recycling plant premises can look welcoming and have an air of professionality for visitors, especially in industrial fields that involve the processing of large streams of unaesthetic biomasses.

It was agreed that social media act as strong visual drivers in advertising actors' sustainability and circularity strategies, as visual transparency cancels faulty preconceptions. Finding influencers within the industry and academia and ensuring their activeness on social media, inputs on visual marketing, sharp name choices, and finding the right audience were also highlighted as important drivers. The current *visual catalogue of nutrient recycling* was regarded as rather generic and boring, with ambiguous demonstrative pictures, such as highly generic industrial plant pictures that have little to do with the nutrient context. Updating and diversifying nutrient recycling-related pictures and visualizing nutrient recycling as an industry requiring advanced technologies, research, and skilled expertise was considered beneficial, rather than merely visualizing piles of manure or other biomasses. Although complex nutrient cycles are challenging to visualize in a simple yet informative manner, one interviewee approached the matter as a resource: Complex yet truthful visualization might push people into realizing how many things need to change. Additionally, a figure illustrating planetary constraints, addressing the flow of nutrients on an even larger scale, could display the urgency of the situation, according to one informant.

#### *4.2.7. Psychological drivers and barriers*

Regarding psychological drivers and barriers, thinking, cognition, emotions, attitudes, and behavior were all identified from our data. *General awareness* of the planet's state and its polluted waters and the ongoing climate change discussion were highlighted, imposing a strong will to change towards more sustainable practices. The importance of solution-based systemic approaches and the benefits of ecosystem thinking as means to promote CE practices were highlighted. However, interviewees acknowledged that systemic change requires a myriad changes on multiple levels and can take generations. Thus, the transition from linear to *systemic thinking* must be maintained through open discussion, information-sharing, good examples, a curious mindset in the face of new obstacles, and engaging everybody as change-makers. For example, sustainability is already embedded in the lifestyle of younger generations: Gradual but evident changes to more curious attitudes and fewer prejudices can be observed, and recycling of various material streams and concern about depleting natural resources are slowly becoming the new norm.

Expectations and social, external pressure were also identified. As general awareness has increased, companies within various operating fields are experiencing external pressure to enhance their sustainability strategy and decrease their environmental impact. One interviewee commented that this can act as a strong driver, for example within the biogas industry – thus boosting the nutrient recycling market – as switching to renewable energy sources can reduce overall emissions. Nevertheless, in certain cases, interviewees felt the external pressure was slightly disproportionate. For example, although the eutrophicated state of the Baltic Sea is the result of past decades' ignorance in farming and industrial activities, the blame often falls on today's farmers, who might be overwhelmed by pressure to change their ways when they lack the resources to do so. Furthermore, mental images based on hearsay can greatly affect consumers' decisions; therefore, different media have the responsibility to convey knowledge and build a truthful mental image.

Consequently, behavior, choices, and preferences as psychological drivers are highly visible in our data. Our interviews highlighted the importance of empowering people to understand the *significance of* their *individual choices*: "*Belittling the significance of one's own actions in the big picture destroys everything. Because recycling consists of countless, extremely small acts,*" one farmer remarked in regard to nutrient recycling. Multiple interviewees emphasized the need to elaborate on the actual benefits that can be achieved through certain actions. For example, the importance of sorting household biowaste and therefore keeping valuable nutrients cycling can be emphasized through sorting campaigns and peer pressure. Some interviewees also wanted food grown with recycled fertilizers to be given a marketing advantage and wished that customers would be prepared to pay a bit more for this trait.

Diverse affects, emotions, attitudes, and concerns were also detected in the data. Certain *prejudices and preconceptions* seemed to prevail. As the recycled nutrient market is still relatively young and small, bad examples by individual actors can tarnish the reputation of the whole industry. *Cultural differences* were also observed concerning *attitudes*. Attitudes towards nutrient recycling and recycled fertilizers were noted to vary largely across Europe, and at national level, people within certain regions were seen as more prone to entrepreneurial spirit and experimentation – urban dwellers were also thought to have more positive attitudes towards nutrient recycling than their rural counterparts, who often need to make actual decisions concerning the fertilizers used on their lands. The food industry's cautious approach and market ban on the use of sewage sludge-based fertilizers and the discussion concerning safety in terms of contaminants, drug and medicine residues, and microplastics were also mentioned, creating concerns and negative emotions such as fear.

## 5. Discussion and conclusions

### *5.1. Summarizing and discussing the key findings: sociotechnical drivers and barriers as catalysts for nutrient recycling at system level*

Our empirical study and analysis of involved actors and their diverse drivers and barriers for nutrient recycling allows us to conceptualize seven thematic categories for sociotechnical catalysts (Fig. 2) that shape nutrient recycling in a national setting. For each catalyst category, several subthemes/categories were identified and conceptualized, that together display the full spectrum of diverse sociotechnical catalyzing drivers for the circulation of critical resources, here nutrients.

We also identified interlinkages and dynamics between positive drivers and negative barriers. We found, firstly that different driver/barrier types interact (e.g. business drives technological development; regulative and technology development trigger of nutrient recycling linguistic development of wordings and terms). To give examples on such interactive dynamics between the barriers, high logistics costs for nutrient reallocation (business barrier) hinder companies and other businesses making profitable business from nutrients, but this business challenge then pushes businesses to concentrate nutrient-rich streams and activates technological drivers by pushing technology developers to advance processing technologies. Secondly, we found that positive drivers or negative barriers can fortify each other and thus form positive driver clusters or negative barrier clusters. One example on how barriers can form negative barrier clusters is that sewage sludge-based recycled nutrients cannot be used in forest management, and their use in agriculture is often hindered as some food industry actors in the Finnish value chain have refused to buy grains fertilized with nutrient originating from sewage sludge. Thirdly, we found that some drivers/barriers can work in a contradictory manner. For example, legislation in Finland does not (currently) unanimously state whether a certain stream is a side stream – meaning that it is easier to convert to recycled nutrient products – or waste; hence, legislation can be either driver or barrier that then can turn to a business driver or a barrier, as it complicates the conversion of a stream to a product and thus the economic value capture from nutrients. Furthermore, farmers' trust in the quality and reproducibility of recycled fertilizer products is low (psychological barrier). This negative example from our case also displays how the regulatory, business, and psychological aspects turn to barriers – instead of drivers - then all together complicating nutrient recycling actions and intentions by the actors. Fourthly, we found that the actors in the same system can perceive, expect and interpret drivers and barriers very differently. Our findings indicate that there might be misalignment of barriers and drivers among the diverse actors. For example, many companies in the value chains for nutrient related businesses formed strategies (management and business drivers) to support recycling of nutrients and showed an interest in supplying and processing them; whereas farmers in the same national actor ecosystem lacked such motivation and incentives to drive change through managing collaboration or business, and preferred to request subsidies/support as a driver to pursue the joint goal of nutrient recycling.

### *5.2. Contributions to theory and practice*

Our exploratory, extensive qualitative case study allowed us first, to develop a new, empirical-based understanding of the actors capable of contributing to nutrient recycling in a regional, national system but with different perspectives on the issue (Fig. 1). The system entails many sector-cutting operations, operates under multiple different ministries, and touches multiple businesses and markets, causing fragmentation of regulations and operations. Secondly, our analysis uncovered the catalysts for nutrient recycling, conceptualized in a framework of different sociotechnical drivers/barriers (Fig. 2) varying from psychological and cultural factors through regulation and business, all individually and jointly shaping nutrient recycling in the system.

These findings contribute to several theoretical discussions. First, by categorizing the catalysts (related to drivers and barriers) that determine the recycling of critical resources (here, nutrient recycling in an urban society), we contribute to CE research discussing barriers to CE (Kirchherr et al., 2018; Ayati et al., 2022) or nutrient recycling in urban society (Akram et al., 2019; Harder et al., 2019; Leipold and Petit-Boix, 2018). Secondly, our empirical analysis of diversified actors contributing to recycling enhances our nascent understanding of CE ecosystems (Aarikka-Stenroos et al., 2021). To date, little research has focused on certain relevant actors in the ecosystem, such as farmers (Kanter et al., 2020); by including farmers, this study found that their decisions are influenced by the legislation, preferences of food-producing companies who serve as their customers, trust in recycled nutrient products, and lack of subsidies to enhance the use of recycled nutrient products. Third, we generated a specific understanding of the societal and cultural side of the CE, particularly in nutrient recycling, by not only focusing on technological processes but answering the research call for investigation of societal perspectives (Kanter et al. 2020, 2020van der Kooij et al., 2020; Metson et al., 2015). Our findings explain what shapes business and societal acceptance of recycled nutrient fertilizers (Cohen et al., 2020; Simha et al., 2021).

Our framework displaying the spectrum of sociotechnical catalysts can also be of use for practitioners, from business and technology developers through policymakers in diverse societies (more and less developed countries) aiming to increase circulation in their national systems. The framework can then guide practical intentions to develop resource circulation, such as nutrient recycling in the focal country: Our findings guide what issues need to be taken into consideration, who to involve in development, and their roles in and potential perspectives on the issue.

### 5.3. Limitations and future research

We acknowledge that our qualitative single case study can have limitations. As our sampling was purposeful, some biases may be present, and other informants could have provided different answers. As a CE ecosystem is a complex phenomenon with an extensive set of actors (Aarikka-Stenroos et al., 2021), it was challenging to determine the (eco)system boundaries of this case study; for example, whether to include or exclude the biogas industry, thus extending the nutrient-recycling system from food production to energy and the traffic industry). As nutrient circulation is highly dependent on farmers, we interviewed some of this group; however, we believe that more research on this actor type is needed to fully understand their role, contribution potential, and difficulties in nutrient recycling. We are also aware that the regional context for recycling nutrient can matter: our case study is conducted in a Northern European setting, and other country contexts may yield different answers. Also the temporal context may matter: the studied actors' awareness on the relevance of nutrient recycling increased along the research process, due to COVID-19 and Russia-Ukraine war.

As our study was qualitative and explorative, we believe that the ecosystem map and catalyst/driver framework developed can encourage researchers to study of actors contributing to CE and driving factors in diverse societal settings and contexts, and also with quantitative research designs. The actor ecosystem map and framework can be used to study diverse CE principles and circulations (e.g., reuse) and resources (e.g., textiles) and thus develop research and pragmatic attempts to advance circularity in all societies of the world.

## CRediT authorship contribution statement

**Leena Aarikka-Stenroos:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Marika Kokko:** Conceptualization, Writing – original draft, Writing – review & editing, Visualization. **Eeva-Leena Pohls:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

This work was supported by the Academy of Finland's "Circular Economy Catalysts: From Innovation to Business Ecosystems (CICAT2025)" research funding (grant ID 320194) and the European Regional Development Fund's "6Aika: ILPO – Climate Positive Business Parks and Value Chains" research funding (grant ID A75909).

## Appendix 1. List of abbreviations

| | |
|---|---|
| CE | Circular economy |
| COVID-19 | Coronavirus disease 2019 |
| EU | European Union |
| $K_2O$ | Potash |
| N | Nitrogen |
| P | Phosphorus |
| $P_2O_5$ | Phosphate |
| REACH | Registration, Evaluation, Authorisation and Restriction of Chemicals |
| WWTP | Wastewater treatment plant |

## Appendix 2. List of interviewees and interview data

| ROLE IN THE ECOSYSTEM | INTERVIEWED ACTOR | POSITION OF THE INTERVIEWEE | TIME AND LENGTH OF INTERVIEW |
|---|---|---|---|
| Authority, administrator | Ministry A | Strategic Advisor | 01/2021, 47 minutes |
| Authority, administrator | Ministry B | Strategic Advisor<br>Senior Specialist | 03/2020, 120 minutes |
| | | Project Manager | 08/2020, 66 minutes |
| Authority, administrator | Authority (fertilizer regulation) | Department manager | 12/2020, 81 minutes |
| Business actor | Biogas producer A | Development Manager<br>Senior Development Engineer | 09/2020, 84 minutes |
| | | Environment & Sustainability Manager | 06/2021, 100 minutes |
| Business actor | Biogas producer B | Environmental Engineer | 08/2020, 54 minutes |
| Business actor | Farm A | Farmer | 01/2021, 70 minutes |
| Business actor | Farm B | Farmer | |
| Business actor | Fertilizer manufacturer A | R & D Manager | 08/2020, 61 minutes |
| Business actor | Fertilizer manufacturer B | Chief Agronomist | 10/2020, 85 minutes |
| Business actor | Food industry company A | Project Manager | 10/2020, 94 minutes |
| Business actor | Food industry company B | Sr. Manager, Grain Purchasing | 09/2020, 73 minutes |
| Business actor | Forest industry company | Senior Researcher | 01/2021, 47 minutes |
| Information provider, advisory service | Professional magazine | Editor-in-Chief | 05/2021, 69 minutes |
| Municipal actor | Waste management company | Development Manager<br>Environmental Specialist | 10/2020, 52 minutes |
| Municipal actor | Wastewater treatment plant A | Project Engineer | 12/2020, 53 minutes |
| Municipal actor | Wastewater treatment plant B | CEO | 08/2020, 31 minutes |
| Municipal actor | Wastewater treatment plant C | Quality & Environmental Manager | 09/2021, 47 minutes |
| Organization, union | Association (biogas and nutrient recycling) | Executice Director | 06/2021, 53, minutes |
| Organization, union | Union (agriculture) | Environmental Specialist, Farmer | 02/2021, 75 minutes |
| Organization, union | Non-profit foundation | Project Manager | 08/2020, 60 minutes |
| Organization, union | Regional development organization | Business Developer | 01/2021, 70 minutes |
| Research institute, university | Research institute A | Senior Scientist | 12/2020, 49 minutes |
| Research institute, university | Research institute B | Sr. Researcher<br>Researcher<br>Researcher | 02/2021, 77 minutes |
| Research institute, university | University | Teacher | 08/2020, 77 minutes |

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