Nutr Cycl Agroecosyst
https://doi.org/10.1007/s10705-023-10285-x

ORIGINAL ARTICLE

Challenges and opportunities for nutrient circularity: an innovation platform approach

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Received: 15 August 2022 / Accepted: 25 April 2023

Abstract To reduce nutrient losses from the food system, it is necessary to improve biomass management and foster change. Such a change is often hindered by a lack of stakeholder interaction. Therefore, a qualitative case study and a practical application of the innovation platform approach in the Dutch-German border region Rhine-Waal were carried out to determine challenges and opportunities in the agro-food-waste system towards circular nutrient management in a nutrient-saturated and intensive animal production-dominated localized area. Twenty-one actors participated in a half-day workshop. A bottom-up approach was chosen as it increases trust between stakeholders and supports the acceptance of research processes. This study identified opportunities and challenges perceived by stakeholders participating in the innovation platform approach to facilitate a transition towards local circular nutrient management. We observed that challenges and opportunities exist at three levels: the individual actor's level, the system level and the interconnection of the system with its wider environment. With a variety of stakeholders from animal and crop production to the food processing industry being present in the study area, the current demand and supply of biomass is very diverse. This diversity has been identified as a distinct opportunity for the establishment of a biomass exchange network in the area. However, information on demand and supply of nutrients between actors is currently scattered and information sharing hindered by the lack of direct monetary benefits. The lessons learned using the innovation platform approach are a first step towards improving nutrient circularity at a localized scale in nutrient-saturated areas.

Keywords Biomass · Agro-food system · Regional · Stakeholder perceptions · Transdisciplinary research

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Introduction

The introduction of easily available and relatively cheap inorganic fertilizers has led to decoupling of previously linked biomass production and the utilization of the containing nutrients for the fertilization

Published online: 05 June 2023

of agricultural land (Kuokkanen et al. 2017; Le Noë et al. 2018). This decoupling facilitated the specialization of entire regions into either animal or crop production and urban or rural areas, respectively (Le Noë et al. 2018). Relatively low transportation costs and low export taxes gave incentive to specialize agricultural production and to extend agricultural trade between geographically separated areas. Specialized agricultural areas depend on external resources (e.g. feed for livestock or fertilizers for crops) (Theobald et al. 2016; van der Wiel et al. 2021), while areas in which crop and animal farming are balanced can recycle biomass locally (Le Noë et al. 2017). These developments in the global food system have changed nutrient management, from local recycling into linear flows, exceeding natural biogeochemical boundaries (Steffen et al. 2015). These altered nutrient cycles have negative environmental and human health impacts (Smil 2000; Van Grinsven et al. 2010). Excessive use of fertilizers can lead to nutrient losses to water bodies and the atmosphere. The nutrients lost from the food system have to be replaced to maintain fertile agricultural soils. However, the future availability of inorganic fertilizers, on which global agriculture highly depends, is uncertain with rising energy prices, increasing fertilizer costs, and some nutrients' availability and accessibility being overall limited (Cordell et al. 2012; Erisman et al. 2008). Further, the disturbance of nutrient circularity[1] is spatially heterogeneous (De Vries et al. 2013). In areas with intensive animal production, nutrient saturation has led to local environmental problems because of manure distribution in excess of plant nutrient demand. One such region is the Dutch-German border region Rhine-Waal.

To reduce issues related to nutrient losses and conserve natural finite resources, it is necessary to improve nutrient management within the whole agro-food system including waste management (agro-food-waste system). The system is responsible for the production, processing and provision of food for human consumption, the processing of biomasses that arise throughout all the system's subsystems, and the emissions to the environment. The system exchanges biomass with its surroundings intentionally and unintentionally, e.g. by export of goods to other areas and losses of nutrients to the environment. But dependency on inorganic fertilizer and feed imports in turn holds the agro-food-waste system in a state of continued imports of biomass (animal feed) and localized environmental issues caused from nutrient access (Kuokkanen et al. 2017). Currently, this system is in a lock-in situation in which it is dependent on non-renewable resources (e.g. phosphate rock reserves, fossil energy derived nitrogen fertilizer) and importing feed to keep up high production levels, while losing nutrients to the environment (Kuokkanen et al. 2017). In this study systemic change was defined as the emergence of a new pattern of organization or system structure aimed to solve the current challenges, e.g. by substantially reduced feed or fertilizer imports. Systemic change can likely lead to a substantial impact on nutrient management through recoupling local nutrient supply and demand (Clarke & Crane 2018).

Bringing multiple actors together holds potential towards addressing system problems in a way in which all actors, including otherwise marginalized, are actively involved and contribute to solving problems and to implementing change (Cullen et al. 2014; Otte et al. 2018; Ravier et al. 2018). The involvement of different actor groups has proven to increase the stakeholders' interest and eagerness to contribute and commonly work on potential improvements (Metson et al. 2012). Learning from each other is considered important for making use of common resources and identifying mutual benefits (Busch et al. 2018; Drejer & Østergaard 2017; McAdam et al. 2016). It is furthermore important for different stakeholders to recognize their shared role in the management of nutrients and to identify barriers (e.g., a lack of legal, economic, and/or social incentives) to facilitate a systemic change (Boulestreau et al. 2021; Metson et al. 2012). To increase trust between the parties and create positive experiences in cooperation, Panten et al. (2018) urged for bottom-up governance frameworks.

Innovation Platforms (IPs) are such a bottom up approach and aim to bring together stakeholders in order to jointly achieve change by overcoming barriers on institutional and organizational levels (Dabire et al. 2017). While the concept of IPs originates from agricultural development interventions in the global South, it has increasingly been applied in a European

[1] Nutrient circularity denotes the internal recycling of nutrients in a region through the use of produced biomasses as sources for food, feed and fertilizers.

context recently, for example to strengthen organizational learning and thereby favor innovation (Stadler & Chauvet 2018; Vehmas et al. 2018). Agricultural IPs are usually initialized by extension and advisory services to enhance interaction among stakeholders to foster agricultural innovation (Sanyang et al. 2016). IPs aim to analyze the complex dynamic situations among several actors facing institutional, legal, economic, and/or social constraints to make use of identified opportunities (Nederlof et al. 2011). IPs have among others been used to foster climate-smart agriculture, to unravel power conflicts, and to assess and improve bioeconomy value chains (Auch & Pretzsch 2020; Osorio-García et al. 2020; Turner et al. 2020). An IP setting offers the opportunity to discuss conflicting views and interests in a structured manner and, at best, actors of the agricultural innovation system recognize shared interests regardless of different motives, which facilitates interaction and knowledge flows resulting in dynamic learning processes and in institutional and social change (Sanyang et al. 2016). Through IPs, challenges and opportunities for fostering change, i.e. a lack of communication and coordination between different actors, can be addressed (Cullen et al. 2014; Nederlof et al. 2011). IPs aim to identify the common needs of a community and based on this, to co-create and initialize change (Sell et al. 2018). Consequently, they are an appealing tool for developing effective policy and to facilitate the utilization of stakeholders' knowledge to restore nutrient circularity.

Previous research highlighted the need for stakeholders stemming from the system under scrutiny to be involved in the process of implementing systemic change and coordinating improved nutrient management (Boulestreau et al. 2021; Dockerty et al. 2012; Heidenreich & Breukers 2020; Metson et al. 2012; Otte et al. 2018; Ravier et al. 2018; Sattler et al. 2022; Vanhamäki et al. 2020). However, the current literature on identification of factors hindering and facilitating systemic change towards circular nutrient management is scarce and shows locally differentiated outcomes (Wojtynia et al. 2021; Wreford et al. 2019; Yadav et al. 2022). For example, Wreford et al. (2019) investigated the transformation towards a bioeconomy in New Zealand and identified challenges and opportunities of system and sectoral integration. The study concluded that support of emerging "niches" and infrastructure and developing a shared vision of a bioeconomy are important and that financial support and governance were lacking in this context. Furthermore, while Wreford et al. (2019) analysed the national scale, insights are missing on the challenges and opportunities experienced by stakeholders of the agro-food-waste system on a localized scale to the best of our knowledge. The current study was carried out to close this gap.

This research therefore aimed to explore the challenges and opportunities in the current agro-food-waste system to move towards a circular nutrient economy in a nutrient-saturated localized area based on local stakeholders' perceptions. Our research adds to the existing knowledge in the following ways: on a conceptual level, it inductively derives, through a process of analytical generalization (Yin 2009), the challenges and opportunities related to transitioning an agro-food-waste-system to higher degrees of nutrient circularity, as perceived by the stakeholders of the system. On a practical level, this study demonstrates the feasibility of an approach to engage stakeholders of a local agro-food-waste system in identifying the challenges and opportunities with regard to a more circular system design. This study, hence, can support comparable areas through providing information on opportunities to make use of and challenges to deal with. The results allow scientific evaluation of other systems and support policy development to facilitate the transition to circular use of nutrients in food production elsewhere.

Materials and methods

A case study was conducted on a practical application of the IP approach piloted in the Dutch-German cross-border region Rhine-Waal. While there is no agreement in the literature on how to establish IPs because of their context-specific nature (Sell et al. 2018), a number of recommendations exist (Dabire et al. 2017; Sanyang et al. 2016; van Rooyen et al. 2017). The approach by Sanyang et al. (2016) was chosen because it provided a clear-cut approach to conduct an agricultural IP. Sanyang et al. (2016) provided a field guide to engage stakeholders and facilitate adoption of innovations. The authors proposed four questions to be considered while conceptualizing IP workshops: "why", i.e. identifying a common purpose and objectives in the study area; "who", i.e.

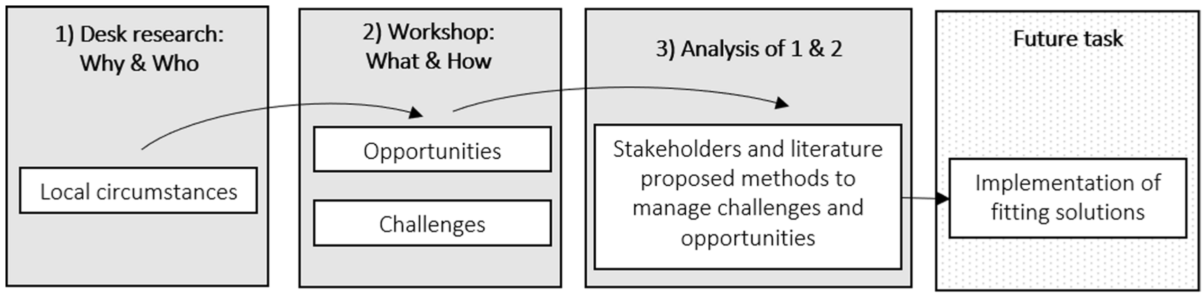

Fig. 1 Illustration of the IP approach used in this study

identifying stakeholders and their direct links along the value chain; "what", i.e. characterizing the complex interactions and knowledge flows; and "how", i.e. identifying new approaches, tools and methods. Figure 1 illustrates the approach used in this research: (1) the desk research answered the "why" and "who" questions through the selection of the case study area and the targeted stakeholders; (2) the workshop dealt with the "what" and "how" questions; (3) the analysis used results from (1) the desk research and (2) the workshop. The outcome of the analysis forms the basis for implementation of fitting solutions in the region in the future.

Desk research

Why: case study area

The study focused on a region at the Dutch-German border, i.e. the Rhine-Waal region, and more specifically the district Cleves in the German state North Rhine-Westphalia, which is an area characterized by nutrient saturation. The district is largely rural, but with several larger urban centers in its vicinity (< 100 km) receiving produced goods and supplying nutrient-rich products in the form of biodegradable fractions of municipal waste and sewage sludge from wastewater treatment plants (Rosemarin et al. 2020). The area is a center of intensive animal production with a high livestock density, conventional cash and vegetable cropping and ornamental plant production. Animal production includes dairy, poultry, pigs and a significant number of privately kept horses (NRW, 2018). On the demand side of nutrient management, there are multiple vegetal cultivation activities, specifically cash crops, such as potatoes, cereals, sugar beet and horticulture, especially field vegetable production. Moreover, the area is known for its extensive food processing industry, processing locally produced and imported raw materials.

Specifically, the intensive animal production sector with large imports of feed, the resulting application of produced manure on agricultural land with nutrient surplus, losses from housing of animals and manure storage as well as cultivation losses from agricultural land requires improved nutrient management. These flows together account for 49% of all nitrogen (N), 51% of all phosphorus (P) and 63% of all potassium (K) flows of the agro-food-waste system in the region (van der Wiel et al. 2021). In 2016, this system exported 2883 t N, 884 t P and 2,114 t K in the form of sewage sludge, compost, manure and organic fertilizers such as digestate, all of which are biomasses rich in plant nutrients and potentially recyclable for fertilization and soil amendment (van der Wiel et al. 2021). Especially the recycling of P in sewage sludge will be subject to change in the future considering upcoming European and German regulations (Sánchez-Cerdà et al. 2020; Sichler et al. 2022). On a mass basis, these biomasses together held the potential to replace 37%, 286% and 565% of the N, P and K imported as inorganic fertilizers, respectively (van der Wiel et al. 2021). However, nutrient management in the local agro-food-waste system is continually linear, from import of feed and fertilizer to export of nutrients in products and manure, as well as nutrient losses or accumulation in the area. Nutrient losses resulting from suboptimal nutrient management lead to multiple local environmental issues, such as eutrophication of ground and surface water bodies which exceeds the standards of the European

Table 1 Target group for focus group dialogue (own elaboration based on van der Wiel et al. (2020) and Spendrup and Fernqvist (2019)

Subsystem	No. of participants	Participating actors
Directly involved with biomass flows		
Crop and animal production (CAP): Crop farmers, animal farmers, farmer consultants, inorganic fertilizer industry	4	Farmers
Food and feed processing (FFP): Food and feed processing companies, feed retailers	4[a]	Amanda Nussverarbeitungsbetrieb, Pfeifer & Langen, Frutarom
Consumption		
Inhabitants, supermarkets	-[b]	-
Waste management (WMA): Wastewater treatment plants, composting plants, municipal waste collection	4	Refood, Schönmackers, Kreis-Kleve-Abfallwirtschaft
Indirectly involved with biomass flows		
Education and research institution (ERI): University, university of applied sciences, research institutes	7	Hochschule Rhein-Waal, Hochschule Bonn-Rhein-Sieg, Wageningen University, FZ Jülich and CLIB
Local authority (LAU): Municipalities, ministries	6[c]	Ministerium für Umwelt, Landwirtschaft, Natur—und Verbraucherschutz des Landes Nordrhein-Westfalen, Gemeente Venray, Agrobusiness Niederrhein, Kuratorium BHD Maschinenring

[a] Only two actors of this subsystem participated in the dialogue

[b] The focus of this research is more on matching biomass flows between businesses, which often are both producers and consumers of biomass. The role of private consumers was not considered in this research

[c] Only five actors of this subsystem participated in the dialogue

Water Framework Directive (Directive 2000/60/EC) (NRW, 2018) in large parts of the area (Wendland et al. 2020). Moreover, the district of Cleves is surrounded by other districts with excess nutrient supply such as the Dutch province North Brabant (Rozemeijer and Broers 2007), which limits the opportunity to transport excess nutrients to areas of nutrient demand nearby.

Covering multiple sectors, such as animal production, food processing and waste management, simultaneously is even more difficult in border regions as different regulations apply and differences in cultural habits affect problem perception by locals (Lundquist and Trippl 2013; Trippl 2010). Fragmentation caused by national borders can not only have a negative impact on gross domestic product (GDP) (Camagni et al. 2017) but also directly affects the operation of enterprises and the efficiency of local resource exploitation by actors in these regions (Capello et al. 2018; Neuberger et al. 2021). Therefore, in border regions changes in the agro-food-waste-system can only be effective if considering a supranational perspective. This makes it an interesting case to study approaches aiming at improved biomass and nutrient management that could serve as a model for other border regions (De Vries et al. 2011).

Who: targeted stakeholders

Targeted attendees for the IP were stakeholders of the agro-food-waste system (Table 1). The selection of participants was considered very carefully as benefits gained from such innovation processes are determined by who initiates, participates in and influences the process (Cullen et al. 2014). Stakeholders were selected from the identified subsystems of the agro-food-waste system where nutrients are exchanged or which represent parties with nutrient supply or demand, such as crop and animal production (CAP), food and feed processing (FFP), consumption, and waste management (WMA) (van der Wiel et al. 2020). Furthermore, local authorities (LAU) and education and research institutes (ERI) are stakeholders who play an important role in the agro-food-waste system to improve biomass and thus nutrient management in a nutrient-saturated agro-food-waste system (Spendrup and Fernqvist 2019).

The stakeholder selection started within the existing network of the authors in the region and was extended through a snowballing procedure to attendees outside the initial network. Of the 24 stakeholders who followed the invitation, 21 participated throughout the whole workshop, of whom 12 were directly and 13 indirectly involved with nutrient flows.

Workshop

During a half-day workshop, we (1) obtained the actors' perceptions regarding their own role in biomass management improvements. By "actors" we refer to the stakeholders that participated in the workshop. Furthermore, we (2) discussed current biomass management challenges and opportunities in the system. We used the term "biomass" rather than "nutrients" during the workshop because it was more commonly used among stakeholders. Yet, biomass management implies the management of the multitude of nutrients contained in it. The terms "biomass" and "nutrients" are, hence, used synonymously in the forthcoming sections. A shortcoming of IP work is often a limited understanding of the underlying concepts or topics of discussion (Cullen et al. 2014). To address this shortcoming, four keynote speakers from Germany and the Netherlands provided insights into current developments of biomass management and additionally, we presented an overview of a generalized nutrient flow chart to the actors to familiarize them with the concept of the agro-food-waste system.

Before the collective part of the workshop started, we made clear that the dialogue was part of a research project and obtained the participants' informed consent. We shared with the participants the objectives of the workshop and made clear that (i) we wanted to learn from their answers and responses, (ii) the workshop is only to exchange experiences and ideas, and that (iii) there are no right or wrong answers. We announced that notes would be made during the dialogue, the insights gained during the workshop will be transcribed and published anonymously and the outcomes will be shared with the participant group upon analysis.

What: perceptions of current biomass management and personal contributions

The perceptions of current biomass management were obtained by asking every participant "How active do you consider your organization to be with regard to biomass and nutrient circularity within the agro-food-waste system?" and, to position themselves on a provided scale (from not active—somewhat active—active—very active). This step was important to develop trust between stakeholders and to build a joint understanding of the current situation in the region. While the existing power relations would hinder problem solving (Turner et al. 2020), IP could be a first step to building trust and the realization that everyone could benefit from nutrient circularity. Such a ranking assignment can be considered a first step of a process of co-creating knowledge as it helps relating the own position to other actors, start developing trust between actors and building commitment to work on specific actions needed to improve the own situation and the whole system (Metson et al. 2012). While the results of quantitative methods to assess nutrient management within the agro-food-waste system such as Substance Flow Analyses (van der Wiel et al. 2020) might not always be in congruence with the system stakeholders' self-assessment and therefore be disputed (Bellarby et al. 2017), our approach allowed actors to explain their position in detail. A team of researchers collected keywords, which were immediately placed, on a pin board as an overview.

How: dialogue of current biomass challenges and opportunities

While the researchers collected these keywords, the participants were further encouraged to discuss the following questions: (a) Where do you see strengths in the agro-food-waste system in the region, and why? (b) Where do you see weaknesses in the agro-food-waste system, and why? Participants shared their experiences and views on current challenges and opportunities regarding biomass circularity to elaborate in which areas actions are needed. The elaborations of one stakeholder often sparked immediate responses by others, and intensive subsequent discussions. Furthermore, the participants were asked to discuss "Where would you place these categories on a scale of "need for action and improvement":

well-developed and strong competitive advantage, immediate need for action?". As a final task of the workshop, we asked the participants, "If we meet again in 10 years and our region has improved significantly, (a) What must happen to get there? (b) How can "strengths" be further developed? (c) How can "weaknesses" be reduced? and (d) How can cross-border cooperation be improved?". All discussions were also captured by the researchers using pin boards and notes taken.

Results

This section elaborates on the "what" question. Perceptions of current biomass management and personal contributions were attained.

The agro-food-waste system (a) is not autarkic and (b) depends on the interaction of stakeholders from the different subsystems. The subsystems are interconnected through the exchange of nutrient containing biomass and the extent to which the system recycles and exchanges biomass between its subsystems indicates its degree of circularity. To explore each actor's role, we asked the participants to position their organization with regard to biomass and nutrient circularity within the agro-food-waste system on a scale from "*Not active*" to "*Very active*". All the actors classified themselves between *"somewhat active"* and *"very active"*. Below, we summarize the reasons for their position, which offer insights on how actor groups see themselves as part of the system.[2]

Among the group of crop and animal production (CAP) actors, participants ranked themselves in *"active"* (n = 3) and between *"active"* and *"very active"* (n = 1). Although they currently already process many residuals from the food industry (e.g. wheat bran), participants of this group were well aware of how much more potential there actually was for improved nutrient management from other residuals of the food processing industry.

In the subsystem waste management (WMA), actors ranked themselves as *"very active"* (n = 1) and between *"somewhat active"* and "*active"* (n = 3). Participants elaborated that their role is to collect biomass and recycle residuals, but the biomass is variable in terms of quantity and quality, which would limit the continuous supply of recycled products at similar quality. Regardless, they still saw a big potential for improvement in the sector through composting food waste from non-household sources (e.g. restaurants) to produce soil amendments with a consistent nutrient content.

The two actors from food and feed processing (FFP) ranked themselves in contrary positions, as *"somewhat active"* and between "*active"* and "*very active"*. The enterprises these actors represented differed in their position in the agro-food-waste system and their size. One actor explained that *we might be too small to make a substantial impact*,[3] which influenced the ranking at *"somewhat active"*.

Education and research institution (ERI) members ranked themselves as *"active"* (n = 2), *"very active"* (n = 3) and *"between active"* and *"very active" (n = 1)*. Participants had an academic background in the fields of animal health, agricultural engineering, waste management, plant production and soil science.

Local authority (LAU) actors ranked themselves as *"somewhat active"* (n = 1), *"active"* (n = 3), and *"very active"* (n = 2), reflecting the diverse set of actors this group was comprised of. A participant from an agricultural networking organization evaluated the individual contribution of its members on nutrient management rather high. This participant considered the organization itself as not having a direct influence on nutrient management. Thereby the LAU participant most likely underestimated their role in connecting individual actors and finding suitable business partners. The two other LAU actors directly in charge of nutrient management positioned themselves as *"active"* because they provided conducive frame conditions through regulations, funding possibilities and networking events between universities and businesses.

Discussion

In this section the "how" question is discussed. Following up on the self-assessment and ensuing

[2] The description of the stakeholder roles is solely based on the participants' input.

[3] Italics refer to literal quotations from respondents, as captured during the discussions.

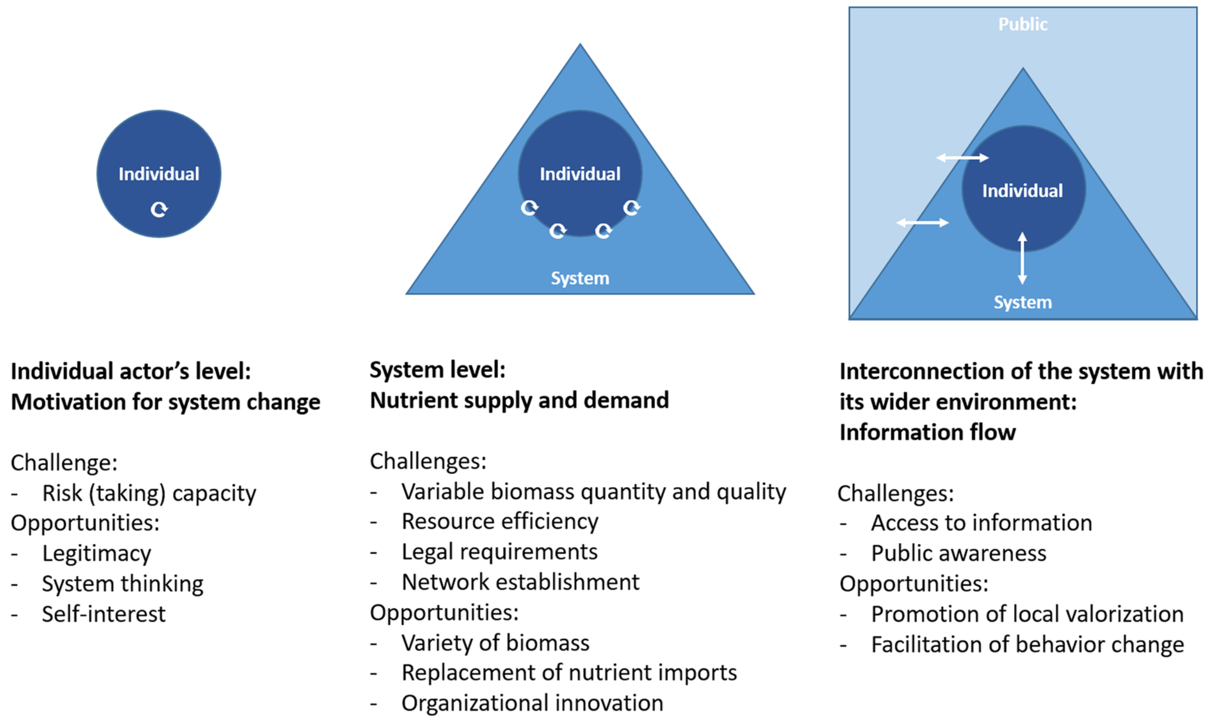

Fig. 2 Challenges and opportunities for actors at three levels

discussions, we identified challenges and opportunities relevant for the establishment of local circular biomass management at three conceptual levels: (1) the individual actor's level, (2) the system level and (3) the interconnection of the system with its wider environment (Fig. 2). The three levels will be explained in more detail by providing the perspectives of system actors.

Actors showed a wide variety of positions

The variety of positions actors placed themselves in reflects the different perceptions among the focus group participants and might originate from existing power relations in the system. It also increases the complexity of the system, making joint action to improve nutrient circularity more challenging. Involving a diverse set of actors might also cause resistance to change in case the perceived costs and benefits of change are unevenly distributed across the different actors. For example, a study of the Dutch agro-food system showed that actors did not agree on how to establish a successful farm business model for agricultural transition as a consequence of such resistance (Wojtynia et al. 2021). In a participatory research on methods for N fertilization management characterized by a similarly diverse pool of knowledge, a divergence of views, experiences, objectives, and level of power, if not managed well, precluded systemic change due to misalignment, disagreement and conflict (i.e. Multi-Level Perspective framework) (Geels 2002; Ravier et al. 2018; Wojtynia et al. 2021). The current linear nutrient management in animal-dominated agricultural areas is largely maintained by the interest of animal farmers who benefit from intensive farming and who use the power they possess to hinder systemic change. However, a diverse set of knowledge may also offer a wider range of available solutions for improvement when successful innovations from stakeholders with little power are heard (Geels 2002).

On an individual actor's level different motivational topics for systemic change exist

We identified four topics, i.e. risk (taking) capacity, legitimacy, self-interest, and system thinking, which provide challenges and opportunities to drive actors to circularity measures in the system.

Risk (taking) capacity is defined as the ability of individuals or organizations to take risk (e.g., by better risk management, or by learning how to assess risk better, including estimation of financial risks). The adaptation of practices by stakeholders towards circularity is associated with risks (de Assis et al. 2017). Stakeholders willing to implement changes need to be capable of handling such risks. Two ERI actors mentioned the *importance of willingness of stakeholders to take risks and invest in transformation in order to achieve systemic change*. However, a major difficulty is the *absence of instruments to reduce risks* for entrepreneurs. An ERI actor recognized *a different attitude towards risks in the Netherlands compared to Germany*, with German stakeholders typically being perceived as more risk averse, which can be a decisive factor for systemic change. Hence, this might also explain the observation of a German WMA actor that *the final implementation* of an innovation *is often conducted abroad*. According to multiple actors stemming from different categories, it is important to *explore methods to reduce risks* to facilitate adaptation towards circularity. Risk (taking) capacity was perceived as a challenge.

Actors experience the desire for legitimacy, defined as the aspiration to meet the expectations of the general public in terms of increased environmental sustainability and quality of food products. For example, CAP actors indicated that they were motivated to strive for circular biomass management by the detrimental health and environmental effects of excess nutrients in so-called “red areas” with e.g. high levels of nitrate in the groundwater. The desire for legitimacy can for example foster change when stakeholders adjust their behaviors and production practices in response to the public no longer accepting local environmental pollution (Bergek et al. 2008; Geels 2002). In such a situation actors may experience that their own and the public´s actions serve the same common goal, which can be a strong motivation to foster systemic change (Metson et al. 2012). An ERI actor and a LAU actor acknowledged that currently there is a big chance to involve people because of their increasing interest in more sustainable lifestyles.[4] Involving society in the establishment of a common goal and the subsequent required system changes supports a better understanding of the system by the public. Hence, the information flow to the public should be improved because behavioral change, such as a change in diet, can support change towards local circular use of biomass (Billen et al. 2018). Legitimacy was perceived as an opportunity.

The approach of actors taking a system-wide perspective is defined as system thinking**.** A problem accounted by a CAP actor considering system thinking is that *the quality of feed is measured by the performance of an individual cow,* which disregards the performance of the system (the farm for example) as a whole. Livestock is predominantly seen as a primary producer of animal-sourced products. However, the actor recognized the *important role of ruminants in a circular biomass system as they produce high-value products from an otherwise low-value product* from other subsystems, i.e. grass. Viewing livestock as adding value to biomass otherwise left unused can appreciate their role in increasing efficiency of the system despite their low feed conversion (Röös et al. 2016). This CAP actor also pointed out that, the area has *an extensive food processing industry, providing food processing by-products which if used as livestock feed, makes the simultaneous presence of livestock and food processing a strength*. However, an actor from food and feed processing (FFP) claimed that *the size of a company influences how much of an impact it can have on systemic changes: if you are small, you have little resources to do something* (on a system level). Furthermore, actors focusing on individual subsystems as single units to achieve internal circularity do not automatically lead to a system-wide circular use of biomass. Wreford et al. (2019) considered it worthwhile to facilitate small projects (“niche efforts”) by bringing these to light, in contact with stakeholders with power, and bundle them to create a common, holistic approach for the whole system. A shift in mindset of stakeholders is required to facilitate system thinking and translation of circularity measures to action, which also requires their involvement through participatory approaches (Luedeling & Shepherd 2016). System thinking was perceived as an opportunity.

When actors consider system changes towards circular biomass management, they reflect whether these changes support their self-interest. Self-interest in this context is defined as maintaining the

[4] The study was conducted in February 2020, when the protests of the “Fridays for future” movement were on their high.

sustainable productive capacity of the individual actor and hence, not damaging business opportunities in the future. While the set of interests surrounding nutrient circularity held by a diverse group of actors in a system-wide, holistic approach may be strongly diverging, avoiding conflict sustains the current linear agro-food-waste system (Turner et al. 2020). Turner et al. (2020) found that only an overarching initiative considering the self-interest of the stakeholders can bridge the gap between subsystems and point efforts in the same direction towards improving circularity. Actors indicated that there are system adaptations that can create win–win situations. For example, a CAP actor said that *areas with red zone status influence local farming, while adapting farming practices in turn can positively influence groundwater status*. This gives farmers actually the opportunity to continue farming in these areas. One such farming practice mentioned is precision farming to increase nutrient use efficiency (Chen et al. 2019; Lal 2002). This results in increased crop yield per nutrient input, while fewer losses occur. Also processing and recycling of locally available biomass into bio-based fertilizers both mitigate local nutrient surplus resulting from the import of required inorganic fertilizers (Case et al. 2017). Case et al. (2017) moreover, found that an incentive for stakeholders to strive for circular practices is the availability of local biomass whereas the future for finite fossil resources is uncertain. Self-interest was perceived as an opportunity.

On a system level different topics influence nutrient supply and demand

Reducing the gap between biomass supply and demand is the main entry point for improving nutrient system circularity. We identified seven topics which provide challenges and opportunities in nutrient flow: variable biomass quantity and quality, resource efficiency, legal requirements, network establishment, variety of biomass, replacing external by internal resources, and organizational innovation.

Biomass quantity and quality is variable (Cooper et al. 2018). A CAP actor acknowledged the *difficulty in predicting biomass availability*. For example, food waste fluctuates seasonally (Hansen et al. 2007). Financial projections of the utilization of these biomasses are therefore difficult to estimate considering quantity and quality, which represents an impediment to forming a corresponding market (Bergek et al. 2008). As mentioned by a WMA actor, for some biomass there is the *issue of scale*, in the sense that locally available quantities are too small to make processing financially profitable. To more effectively anticipate biomass supply and demand, more reliable data is needed (Cooper & Carliell-Marquet 2013). We derive that matching supply and demand requires the awareness of both sides that depend on and benefit from the exchange of biomass. A local communication platform, which allows for matching demand and supply of various biomass streams in quantity and quality could be a mean of improving local circularity. Such a biological resources hub (BioRes Hub) has partially already been implemented for nutrient exchange (e.g., Nährstoffbörse NRW; www.naehrstoffboerse.de). Variable biomass quantity and quality was perceived as a challenge.

Resource efficiency, i.e., utilizing by-products from food production, processing and consumption, is of great importance to improve circularity (de Boer & van Ittersum 2018). As mentioned by a CAP actor *crop requirement adjusted fertilization using processed biomass as fertilizer is required*. Efficient utilization of biomass such as manure, a nutrient-rich by-product of the animal production subsystem, can increase resource use efficiency on a system-wide level. Manure can be processed to yield bio-based fertilizers that can be applied to agricultural soils instead of inorganic fertilizers, thereby reducing nutrient imports and increasing nutrient uptake efficiency by plants (Tur-Cardona et al. 2018). However, animal production is inherently inefficient, even when the manure produced is valued equal to the animal-based products. A part of the N in feed supplied to animals is always lost during housing and during storage of manure (NRW, 2018). Because of the animal-dominated agriculture in the study area, increasing local nutrient use efficiency is challenging. Similar to our case study area, agriculture in New Zealand is dominated by animal production not integrated with crop production (Wreford et al. 2019). This challenge can be tackled by using animals for what they are good at (de Boer & van Ittersum 2018), such as using by-products from the processing industry as feed (Röös et al. 2016), or utilizing land otherwise not suitable for food production like pasture or meadow. Thereby, biological resources of lower economic value for farmers can be converted into higher value animal-sourced products, turning livestock in a system from a weakness into a vital aspect for circularity (Van Zanten et al. 2018). Ruminants are specifically efficient in utilizing grassland, whereas monogastrics, such as pigs and poultry, can utilize food processing by-products (Röös et al. 2016). The balance between crop and animal production can be restored by fitting the livestock numbers (Billen et al. 2021; Desmit et al. 2018) to the locally available feed resources (grassland, feed crops and food processing byproducts).

Actors from ERI, WMA and LAU agreed that the **legal requirements** and infrastructure frame conditions have to be adjusted to allow the transition from a linear to a circular system. An apparent case is sewage sludge, where the exchange across the German-Dutch border is currently complicated by the existence of incongruent regulations on either side. An example provided by a WMA and a LAU actor is *the declaration of biomass (e.g. waste vs. by-product)*, which *is different in the Netherlands and Germany.*[5] Legal differences can complicate cross-border cooperation (Borges et al. 2022; Camagni et al. 2019). Hence, legal requirements were perceived as a challenge.

Similar difficulties exist in establishing a common network (cross-border) supporting the exchange and circular use of biomass. To establish a network which will remain, transparency about the problems experienced in the past and development of an overarching common goal are important (Metson et al. 2012). A WMA actor confirmed that a network has to solve concrete problems experienced by the stakeholders of the system to remain. A problem is that different and sometimes even contradicting problems exist in different areas, e.g. nutrient surplus vs. deficiency. This underlines the importance of fostering participation of farmers in an exchange network about nutrient management (Boulestreau et al. 2021). Previous research stated that contradicting problems can offer an opportunity by matching each other's supply and demand through assessing flows on a multi-local level (see also Cooper and Carliell-Marquet (2013)) and providing an exchange platform similar to the BioRes Hub mentioned above. Hence, network establishment was perceived rather as a challenge than an opportunity.

In the case study area, a large variety of biomass is available, such as by-products from food processing, organic household waste, municipal and industrial wastewater, manure from animal production and leftovers from crop production. To be able to utilize existing streams efficiently, the streams need to be identified, quantified and qualified in terms of their nutrient content (van der Wiel et al. 2020). A WMA actor recognized the great potential of processing their input, organic fraction of municipal solid waste, to recycle the contained nutrients through composting back to agriculture. Furthermore, an actor of the FFP mentioned that there is biomass available, which represents a byproduct for one actor but are a valuable raw material for another. According to an ERI actor, it is also important to explore higher-value utilization of biomasses. Utilizing by-products from the food processing industry, for example, as feed rather than composting, adds value to it through the production of animal-sourced food (Röös et al. 2016). Actors considered that the variety of biomass sources and suppliers was a "strength" that can be further exploited to approach or restore local nutrient circularity.

The utilization of locally available biomass to replace nutrient imports is one of the principles that must be adhered to in order to achieve circularity in the food production system (de Boer & van Ittersum 2018). When more input into subsystems is sourced internally, import can be reduced, and surplus of nutrients within the area, and subsequent environmental issues are lowered. Continued import of feed contributes to the surplus in the system. A mass balance is required to determine the desired balance between different activities representing supply and demand in the system (van der Wiel et al. 2021). By an actor of the FFP, wastewater from commercial sources was viewed as a valuable, currently underutilized source of nutrients which could be recovered to provide bio-based fertilizers to replace currently imported inorganic fertilizers. Currently, municipal wastewater is not recycled back into agriculture due to contamination risks with e.g. human pathogens or pharmaceutical residues and therefore the legal framework does not allow it. However, different approaches to recycle phosphorus from sewage sludge already exist, such as Struvite or Calcium phosphate precipitation

[5] This has been arranged on EU level by the new Fertilizer ordinance.

(Sánchez-Cerdà et al. 2020; Sichler et al. 2022). In the near future as by new regulations, phosphorus needs to be recycled from wastewater in Germany. According to a CAP actor, a potential change in animal production could be established due to progress made in feed processing. A crop grown in Europe, i.e. oilseed rape, can be locally processed into oilseed rape press cake that has a similar nutritional value like soy, which is currently imported from South America. Replacing nutrient imports was therefore appreciated as an opportunity to contribute to more circular biomass management.

For companies to move towards circularity they will have to innovate their business models on an organizational level (business model innovation). As already mentioned, collaboration is important to facilitate behavioral change and hence coordination between existing stakeholders and/or across networks is needed, implying the need for organizational innovation (Metson et al. 2012). According to one WMA actor, food leftovers are generated spatially scattered, and their processing will require innovations in biomass collection schemes besides technological innovation. A LAU actor stated that new business models are essential to make innovations economically interesting on the system and individual company scale. Organizational innovation was perceived as an opportunity.

The flow of information decides the interconnection of the system with its wider environment

We identified four challenges and opportunities, i.e. access to information, public awareness, promotion of local valorization, and facilitating behavioral change.

Access to information was considered a challenge within the agro-food-waste system and to the wider public. Participants indicated that sharing of information between stakeholders on their biomass supply and demand and information about farm management issues and solutions can facilitate the efficient exchange of biomass (Boulestreau et al. 2021). Another difficulty faced by participants concerned the complexity of the topic "circular use of biomass" which makes it difficult to communicate its role and the importance of related actions. Different stakeholders can understand and perceive the concept of circular use of biomass differently, which was also observed by Giurca (2022) when communicating the topic "circular bioeconomy". For example, one ERI actor sees a burden that many customers *do not have common knowledge and do not know what plastic is made of* while such basic knowledge is essential to understand the importance of circular use of biomass. Co-creation of strategies with stakeholders responsible for putting scientific knowledge into practice can increase the awareness and required knowledge among stakeholders (Rhisiart et al. 2015). Moreover, co-creation would facilitate higher levels of data provision by stakeholders and a full inventory on locally available processing technologies for biomass as well (Metson et al. 2015). The element "access to information" was considered a weakness that needs to be improved in the next 10 years to achieve local nutrient circularity.

Municipalities were considered as active in forcing system change by stakeholders, but an ERI actor complained about the *lack of* public awareness *in society about the significance of circularity in the value chain and its importance for keeping additional value in the region, i.e. through additional jobs.* The lack in public awareness could lie in the growing distance between food production and consumers. It is therefore important to focus on changing the system integrally, including aspects such as market development for products produced in a circular system. WMA actors and FFP actors acknowledged that there is *a solid foundation of ongoing research in the region* while the difficulty remains *how to implement the findings in practice*.

Local valorization of resources requires promotion through improved access to information, communication and cooperation throughout the system. Local processing to valorize biomass is preferred as opposed to transporting it to areas with a demand, not least as biomass is generally bulky with a high water content making transport inefficient and costly (NRW, 2018; van der Wiel et al. 2021). Communication between different farmers would allow estimation of imported farm inputs and possible local substitutes. Communication between other stakeholders can further foster circularity; a FFP actor mentioned that *local valorization is possible in some enterprises through processing commercial wastewater in an on-site wastewater treatment plant*. Local valorization of biomass can be achieved by using locally available manure rather than exporting it (NRW, 2018). Hence, an opportunity lies in developing an inventory of locally available and required biomass resources for setting up a corresponding information and exchange network (van der Wiel et al. 2021).

A WMA actor mentioned that it is important that household waste is separated well to efficiently recycle nutrients in food waste, which requires facilitation of behavioral change. Consumers would have to better separate household waste. It was considered necessary for scientists and politics *to actively participate in the region and to not wait for the public to initiate* behavioral change.

However, behavioral change or societal pressure can also drive the system to consider e.g., environmental issues or animal welfare (Geels 2002). For example, short supply chains can be established from primary producers to consumers in which actors agree to provide stability for the system and to invest in such issues. Actors agreed that such *networks do not need to be created from scratch as opportunity lies in the already established independent networks in the region*.

Research limitations

The focus of the present study was to illustrate the initiation of an IP approach and showing its potential to decipher challenges and opportunities of local nutrient circularity as perceived by stakeholders from different subsystems within the agro-food-waste system. Following Nederlof et al. (2011), our explorative research did not aim to identify and evaluate actions potentially undertaken to achieve nutrient circularity. It was also beyond the scope of this study to provide solutions for improved nutrient management or establish cooperation between stakeholders. In the course of this study, an IP approach was initiated, while the progress towards self-coordination of actions by participants was beyond the timeline of this study.

Moreover, while asking actors about their involvement in implementing circularity, we did not intend to investigate power relations between actors during the workshop. As existing power dynamics might hinder the transition to circular nutrient management if stakeholders with power use this to sustain the current system, while other stakeholders are not given space to demonstrate the success of adaptations (Geels 2002; Wreford et al. 2019), power relations should be considered when selecting stakeholders for IPs in the future.

Actor's positioning on the "active" to "not active" continuum is subjective. All actors in this study perceived their role as at least rather active and the challenges and opportunities perceived might be skewed. In this study, the participating actors were forerunners of circularity and as such directly or indirectly involved in the exchange of biomasses already. A limitation might originate from the composition of the workshop participants, i.e., a lack of non-active actors and the underrepresentation of actors from the crop production subsystem and of large food and feed processing companies, while ERI and LAU were over-represented. Hence, results may not be fully representative for the agro-food-waste system in the region.

Conclusions

This study explored the utilization of participatory IPs to determine challenges and opportunities in the agro-food-waste system towards a circular nutrient economy and nutrient cycling in a nutrient-saturated localized area. This study provides evidence of the applicability of the participatory IP approach for identifying challenges and opportunities towards nutrient circularity. This study hence benefits similar efforts in other, comparable regions and thus can support the transition to circular use of nutrients in agro-food-waste systems.

A strong need for action was observed with regard to information flows. Currently, information on improved biomass management practices hardly transitions from research to practice and the wider public. The participatory IP has shown that lack of information flows also influence the public perception of circularity. Especially considering the location of the case study area and its ties with the Netherlands with regard to biomass flows, the information exchange needs to be cross-border. Further research is necessary to identify the economic costs, risks and benefits of such coordination and information infrastructure (e.g. BioRes Hub), how it could be financed through service charges or other instruments, and which regulatory changes are required to assure its cross-border accessibility.

A strong opportunity for the area under study has been identified to lie in the diversity of subsystems and their available biomass, sourced from the localized area also across the border. Improved access to information on the diverse subsystems' nutrient supply and demand can further facilitate this opportunity for the region to become more circular. Even though actors of different subsystems seem to be willing to cooperate and learn from each other, it is not easy to involve them on a long-term basis as the immediate benefit of cooperation is currently not visible to them. By documenting an application of the participatory IP approach we demonstrate that stakeholders can identify mutual opportunities and current bottlenecks as a basis of future collective action.

Acknowledgements This work has been carried out within the Interreg funded Food Pro.tec.ts project. Bernou van der Wiel's and Sabine Neuberger's PhD researchers are furthermore financially supported by the Deutsche Bundesstiftung Umwelt and the Wageningen University, respectively. The authors are grateful to Verena Kröner for the assistance provided during the workshop, and two anonymous reviewers whose comments helped to further improve the manuscript.

Declarations

Conflict of interest All authors declare that they have no conflict of interests.

Informed consent Informed consent was obtained from all individual participants included in the study.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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