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Review

Reframing human excreta management as part of food and farming systems

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A B S T R A C T

Recognition of human excreta as a resource, rather than as waste, has led to the emergence of a range of new and innovative nutrient recovery solutions. Nevertheless, the management of human excreta remains largely rooted in current sanitation and wastewater management approaches, which often makes nutrient recovery an add-on to existing infrastructures. In this paper, we argue that framing human excreta management as a resource recovery challenge within waste management obscures important trade-offs. We explore the factors that would be brought to the fore by reframing human excreta management as part of food and farming systems. We find that such a reframing would accentuate (at least) six aspects of critical importance that are currently largely overlooked. Recognizing that the proposed framing may also have its limitations, we argue that it has the potential to better guide human excreta management towards long-term global food, soil, and nutrient security while reducing the risk of compromising other priorities related to human and environmental health.

Contents

1. Introduction

Finding ways to feed a growing and increasingly urbanized population while reducing environmental and social impacts is a major global challenge (Foley et al., 2011; Willett et al., 2019). One of the key prerequisites to achieving and maintaining global food security is improved nutrient management along the entire food

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chain, which includes farming practices, food processing, consumer behavior, and waste management (McConville et al., 2015). Better nutrient management also includes the recirculation of nutrients from human excreta to food production (Drangert et al., 2018; Trimmer and Guest, 2018). In most cultures, human excreta has historically been used for fertilization and soil improvement (Ferguson, 2014). However, the introduction of the water closet and sewer networks (that is, waterborne sanitation) has led to a decoupling from food production (Ferguson, 2014). Other contributing factors are increased urbanization and the industrialization of farming systems (Jones et al., 2013), characterized by specialization and widespread use of mineral fertilizers and pesticides. Taken together, these factors have profoundly altered nutrient flows at the local, regional, and global scales, leading to a linearization and globalization of nutrient flows as illustrated and explained in Fig. 1.

It has become increasingly evident over the past few decades that the patterns of nutrient flows associated with current approaches to farming and human excreta management are unsustainable (Steffen et al., 2015). Global estimates of current recirculation rates are highly variable, but suggest that, at most, 15 percent of nitrogen and 55 percent of phosphorus in human excreta are recirculated to cropland (Trimmer et al., 2017). Also, emissions of nutrients from human excreta to water bodies are projected to increase even further in the future due to increased population and urbanization (van Drecht et al., 2009), as well as the widespread perception of waterborne sanitation as the ‘gold standard’ (del

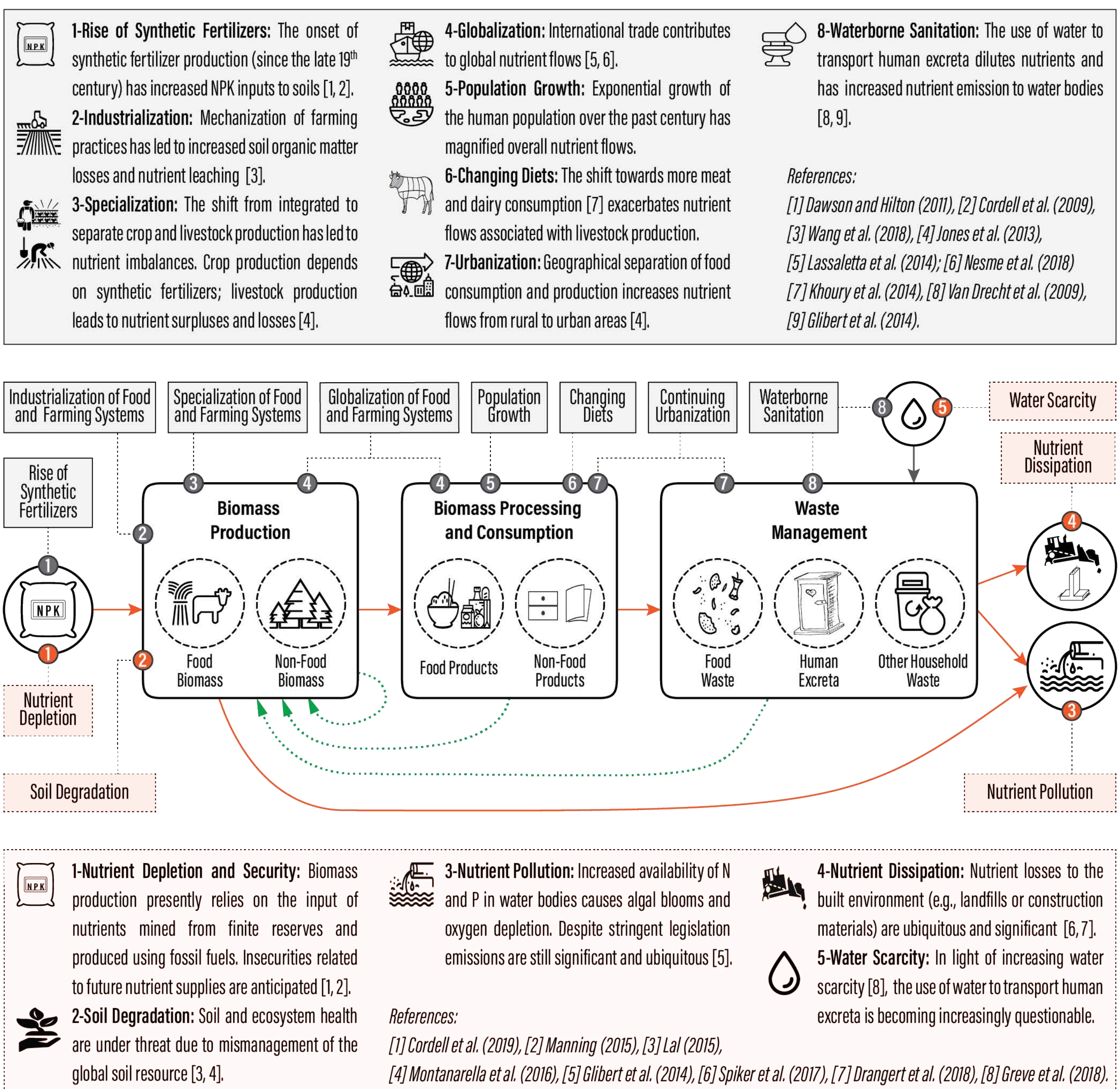

Fig. 1. Drivers and environmental problems associated with the linearization and globalization of nutrient flows. Orange solid arrows: linearization and globalization of nutrient flows. Grey solid boxes: associated drivers. Orange dotted boxes: associated environmental problems. Green dotted arrows: opportunities for nutrient recirculation (Greve et al., 2018; Lassaletta et al., 2014; Nesme et al., 2018; Spiker et al., 2017).

Carmen Morales et al., 2014). Concerns about nutrient pollution in freshwater and marine environments (Glibert et al., 2014), combined with the anticipation of insecurities related to future phosphorus supplies (Cordell et al., 2009), have fuelled the development of new and innovative human excreta management solutions that facilitate the recovery of nutrients (and organic matter) from human excreta for reuse in agriculture (Haddaway et al., 2019; Harder et al., 2019).

The development of nutrient recovery and reuse solutions reflects an ongoing shift from perceiving human excreta as waste towards recognizing its value as a resource, and is part of a broader trend towards more comprehensive resource recovery in the sanitation and wastewater management sectors (Larsen and Gujer, 1997; Otterpohl et al., 1997; Wilsenach et al., 2003; Larsen et al., 2009; Verstraete et al., 2009; Peccia and Westerhoff, 2015). Several scholars have in fact highlighted that new and innovative sanitation and wastewater management solutions that embrace resource recovery have the potential to enhance multiple ecosystem services (Trimmer et al., 2019a) and contribute to the achievement of multiple sustainable development goals (SDGs) (Andersson et al., 2016; Andersson et al., 2018; Trimmer et al., 2017; Orner and Mihelcic, 2018). Although human excreta is increasingly recognized as a resource, its management is still largely rooted in current sanitation and wastewater management approaches (Simha and Ganesapillai, 2017). Under these premises, nutrient recovery often becomes an add-on to existing infrastructures.

It is well documented that the way in which an issue is framed has a major impact on the perception of what the problem is and how it might be handled (Vliegenthart and van Zoonen, 2011; Halffman, 2019). We acknowledge that a reframing of human excreta management could take many forms and would like to highlight that any framing – whether implicit or explicit – will inevitably lead to certain aspects and perspectives being prioritized over others. Recognizing that this is also true for the proposed framing, we argue that reframing human excreta management as part of food and farming systems has the potential to shift the perception of opportunities and challenges and can reveal central trade-offs that are currently underrated.

Since vocabulary guides our thinking (Schön, 1993), we believe that a shift in thought patterns and framing also requires a shift in terminology. Much of the current vocabulary related to human excreta management is rooted in the perception of human excreta as waste and contributes to the technological, institutional, and mental lock-in to conventional solutions. For example, the terms ‘human waste’ and ‘wastewater’ directly allude to the notion of ‘waste’. Similarly, the term ‘sewage’ requires sewers and ‘wastewater’ implies the use of water as means of transportation. Therefore, we have chosen to avoid these terms and consistently speak of human excreta, streams that contain human excreta, and human excreta management.

2. Underrated aspects of human excreta management that reframing brings to the fore

There are natural linkages between agriculture, food, and human excreta management. We find that reframing human excreta management as a part of food and farming systems would give prominence to (at least) six aspects that are currently largely overlooked, as illustrated in Fig. 2. We propose that better consideration of these aspects has the potential to contribute to global food, soil, and nutrient security in the long term. The six underrated aspects are elaborated upon below. While presented separately, they are connected and there are potential synergies among them.

2.1. Prioritizing nutrient recovery and reuse

Globally, the potential contribution of nutrient recovery to meet fertilizer demand far surpasses the potential contribution of energy recovery to meet energy demand (Trimmer et al., 2017). Even so, energy recovery from human excreta has long received more attention than nutrient recovery (Grant et al., 2012; van Loosdrecht and Brdjanovic, 2014). Moreover, recent research and development of novel energy recovery technologies that use streams containing human excreta as feedstock for the production of biocrude, bioethanol, biodiesel, biohydrogen, and syngas (Gomaa and Abed, 2017; Puyol et al., 2017; Manyuchi et al., 2018) has rarely indicated what fraction of nutrients, if any, is recovered in parallel and in what types of residual products. From a longer-term nutrient security perspective, globally, the role of human excreta-derived nutrients in supplying nutrients to biomass production should not be understated and it would be important to weigh the contributions of energy versus nutrient recovery in relation to their respective demand. We acknowledge that resource recovery in sanitation systems can provide multiple benefits in different local contexts, including contributions to energy supply and building soil organic matter (Crews and Rumsey, 2017).

2.2. Broadening the scope of nutrient recovery

Plants need at least 17 essential elements to grow (Hänsch and Mendel, 2009; Maathuis, 2009). Certain other elements, even if they are not essential for plant growth, can be essential for animal nutrition, such as cobalt (Voortman, 2012), or human health, such as selenium (Jones et al., 2017). Insufficient and imbalanced fertilization has led to a systematic stripping of nutrients from soil at the global level (Jones et al., 2013). For instance, potassium limitation is common in terrestrial ecosystems globally (Sardans and Peñuelas, 2015) and it has been estimated that only about half of the potassium removed from soil as offtake is replenished through fertilizers and soil amendments (Sheldrick et al., 2002; Manning, 2018). Concerns have also been raised regarding micronutrient stripping (Voortman, 2012; Jones et al., 2013) and micronutrient deficiencies, notably regarding copper, zinc, and selenium (Udo de Haes et al., 2012; Jones et al., 2017).

The depletion of high-grade phosphate rock deposits has led to increasing attention being given to alternative phosphorus sources. Several jurisdictions have implemented legislation for comprehensive phosphorus recovery (such as Switzerland [VVEA, 2015], Germany [AbfKlärV, 2017], and Austria [BAWP, 2017]), or are in the process of developing such legislation (Sweden, for example). However, potassium and micronutrients are also currently mined from finite deposits. Some scholars have argued that potassium is not anticipated to be in limited supply, nor is there a significant energy requirement for the production of potassium fertilizers (Dawson and Hilton, 2011). Others have highlighted that high-grade potassium ore is also limited and concentrated in a small number of countries, and have advised the exploration and use of novel sources of potassium (Ciceri et al., 2015; Manning 2015, 2018). Likewise, micronutrients might become increasingly scarce (Voortman, 2012). In contrast, nitrogen is not in short supply as it is abundant in the atmosphere. Key challenges are to minimize losses of reactive nitrogen to the environment and to develop less energy-intensive ways of nitrogen fixation from the atmosphere (Razon, 2018).

There is little doubt that phosphorus recovery plays a critical role in slowing down the depletion of high-grade phosphate rock deposits. However, a narrow focus on phosphorus recovery falls short of addressing the broader issues of soil nutrient stripping, increased micronutrient deficiencies, and long-term food security.

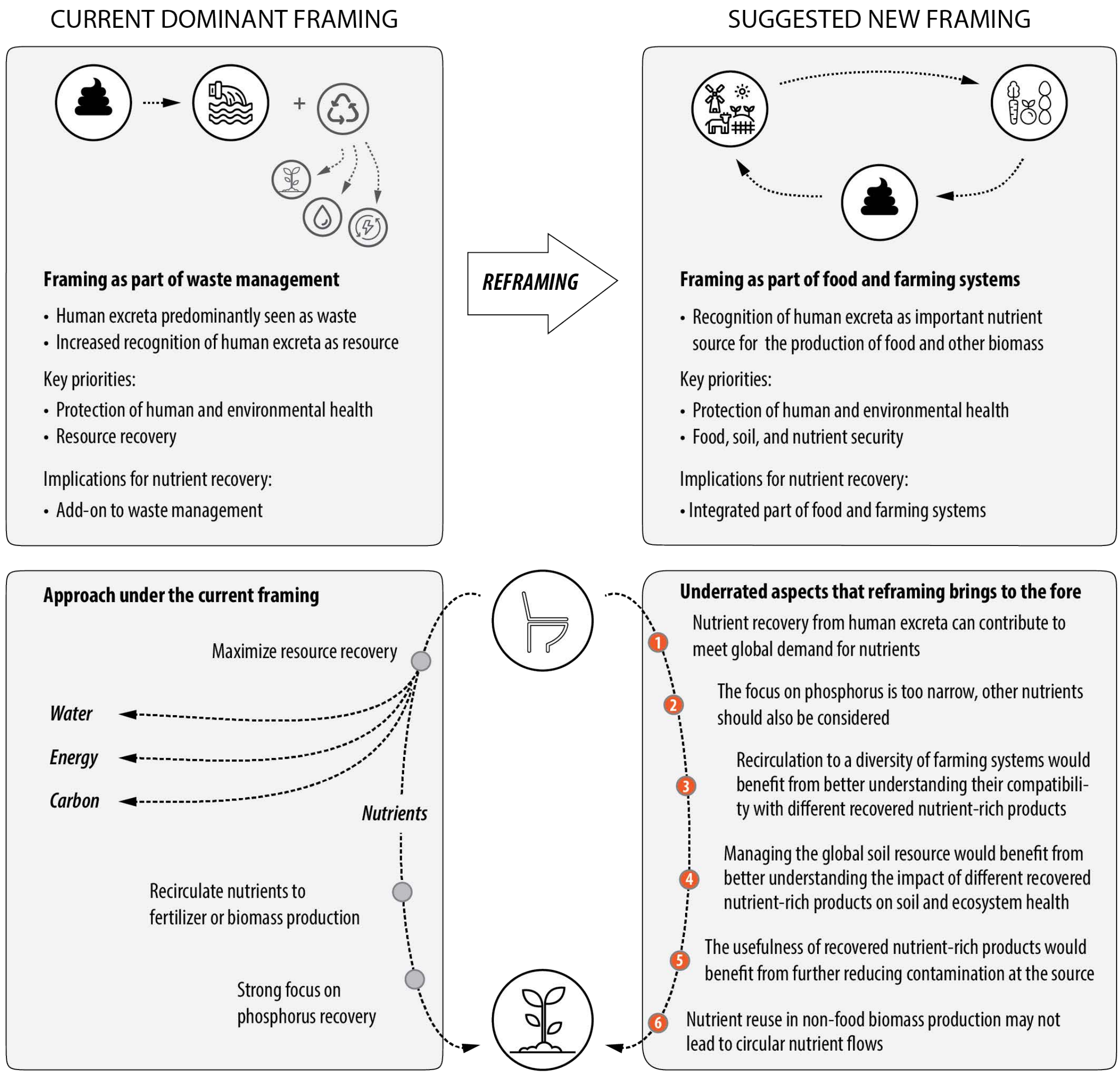

Fig. 2. Current and proposed framing of human excreta management, as well as, underrated aspects of human excreta management that emerge upon reframing.

Many recovery technologies that have focused on phosphorus recovery have actually resulted in high losses of other nutrients (such as nitrogen to the atmosphere and potassium to the effluent). Therefore, there is a risk that an overly narrow focus on phosphorus may lead to sub-optimal solutions. From a longer-term sustainability perspective, there are reasons to include potassium and micronutrients (and possibly nitrogen, to reduce energy requirements and minimize the introduction of new reactive nitrogen into global nutrient cycles) in efforts to increase recirculation of nutrients contained in human excreta (and other organic residuals) to biomass production, as is already the case for some of the recovery and reuse technologies and approaches that are under development (Harder et al., 2019). We recognize that recovery of multiple nutrients carries various challenges, including trade-offs such as energy requirements or the quality of the recovered product with respect to for example product homogeneity, plant availability, and environmental contamination.

2.3. Catering to diversity in agricultural production

There is fierce debate on what the future of food should look like (Garnett, 2014; Fraser et al., 2016; Willett et al., 2019). Because it is highly unlikely that one single solution will work in all locations, we assume that a combination of different types of production systems will be required (Cunningham et al., 2013). The future food system will likely include ‘soil-based’ production systems (where soil is the growth medium) as well as ‘soil-less’ production systems (where substances other than soil are the growth medium), varying from low-tech to high-tech, and located in rural as well as urban settings. Among the soil-based production systems, there will most likely be scope for a wide range of systems that are adapted to the local ecological conditions and resource base (Struik and Kuyper, 2017). Among the soil-less systems, there are opportunities for hydroponics and aquaculture in various configurations, including vertical farms (Muller et al., 2017), as well as, reactor-based production of microbial protein (Pikaar et al., 2017; Linder, 2019). The variety in production systems for food (and other biomass) will require a variety of nutrient inputs. Hydroponic production systems, for instance, require a carefully crafted combination of mineral salts to produce a nutrient solution, possibly in combination with granular fertilizers such as struvite. Aquaculture systems require fertilizers or fish feed, which could contain protein rendered by treatment of streams containing human excreta. In principle, soil-based production systems can handle a wide variety of nutrient inputs, ranging from nutrient-rich liquids and organic matter to granular and powdery inorganic matter, although different soil-based production systems and different farmers have different preferences. In other words, there will most likely be a need for a wide array of nutrient-rich products rendered by treatment of, among other organic residuals, streams containing human excreta (henceforward referred to as nutrient-rich products).

Until very recently, however, most research on developing and assessing nutrient recovery and reuse solutions was not designed to meet the needs of specific production systems. This is probably because nutrient recovery and reuse is seen primarily as a way to replace conventional mineral fertilizers and curb the demand for mined nutrients. However, different ways to produce biomass differ widely regarding environmental and social impacts (Hilborn et al., 2018; Poore and Nemecek, 2018; Rasmussen et al., 2018). If the overarching question is how human excreta management can best support future agricultural production, as opposed to how to best replace conventional mineral fertilizers, it becomes important to distinguish between different human excreta-derived nutrient-rich products and clarify their usefulness for different ways to produce biomass. This includes aspects related to the characteristics of the recovered product (for example nutrient composition, solubility, and availability) and potential constraints (for example soil characteristics, fertilizer application practices, nutrient use efficiency, or farmer preferences). Viewing nutrient recirculation as an integral part of long-term food and nutrient security therefore highlights that better understanding of the compatibility of different nutrient-rich products and production systems is key to ensure that nutrient recirculation can cater to a diversity of farming systems.

2.4. Invigorating soil and ecosystem health

The global degradation of arable soil is a major challenge to food security and agricultural sustainability (Montgomery, 2007; Amundson et al., 2015; Montanarella et al., 2016). It has been proposed that the concept of soil security can better translate soil science into policy for sustainable development (Koch et al., 2013) by actively promoting management practices that mitigate soil degradation, notably erosion (Baumhardt et al., 2015; Lal, 2015), and regenerate soil health (Sherwood and Uphoff, 2000; Cardoso et al., 2013). In this regard, the role of soil biodiversity for sustaining or improving food supply and human health has been emphasized (Wall et al., 2015), with several scholars calling for soil and land management practices that promote soil biodiversity (Wall et al., 2015; Bender et al., 2016). Ultimately, to help protect the global soil resource, nutrient-rich products (including those that contain human excreta-derived nutrients and organic matter) will need to be compatible with farming practices and production systems that maintain or improve soil and ecosystem health. This goes beyond just replenishing inorganic plant nutrients and relates more broadly to farming practices and production systems.

Agronomic evaluation of (recycled) fertilizers has long focused primarily on nutrient availability, nutrient uptake, and crop yield. Testing often takes place in pot experiments, which means it does not allow for a differentiated evaluation of fertilizers in the broader context of soil and ecosystem health at the field and landscape scales. Therefore, a better understanding of the compatibility of different nutrient-rich products and biomass production systems is crucial to guide the development and assessment of recovery and reuse of human excreta-derived nutrients towards invigorating soil and ecosystem health. Recent research into the effects of (recycled) fertilizers on microbial communities and soil biodiversity (van der Bom et al., 2019; Ibekwe et al., 2018; Staley et al., 2018), and into the alignment of recycled fertilizer chemistry with local soil properties (Trimmer et al., 2019b), are important steps in this direction.

2.5. Further reducing contamination at the source

Contaminants that are found in human excreta or added from other sources to streams containing human excreta include pathogens as well as a variety of inorganic and organic substances such as industrial chemicals, pharmaceuticals, personal care products, and other household products. These substances represent a major challenge when it comes to recirculating human excreta-derived recycled fertilizers to agricultural production, since their presence restricts the use of these products (Mininni et al., 2015; Röös et al., 2018). Evaluating the risks involves many uncertainties and concerns have been raised that potential undesired effects are yet to be discovered. The increasing concerns regarding substances that interact with the hormonal system (endocrine disrupting chemicals, EDCs) and their association with a diversity of adverse effects in wildlife and humans (Damstra et al., 2002; Bergman et al., 2013) are of particular importance.

Broadly, contamination of human excreta-derived nutrients can be reduced by preventing the use and emission of potential contaminants or by influencing their fate during collection and treatment of human excreta. Measures to control emissions, for instance, have led to a significant reduction of heavy metal concentrations in sewage sludge in Sweden from the 1970s onwards (Kirchmann et al., 2017). Controlling emissions of other substances is more difficult since the number of such substances is orders of magnitude larger than that of metals. Separate collection of human excreta, without mixing with domestic and industrial used water or stormwater, has the potential to limit contamination to only the substances present in human excreta. Separate collection of human excreta may, however, not be feasible or preferable in all situations and places, for instance with regard to existing infrastructures, investment costs, or user preferences. While several treatment processes exist that can partially or fully remove or break down some of the organic compounds of concern, high operation costs and the formation of by-products remain a challenge (Luo et al., 2014). Moreover, complete decomposition of organic compounds often results in loss of volatiles containing carbon, nitrogen and sulfur.

Nutrient recirculation would benefit from further efforts to reduce or avoid contamination of human excreta at the source and during collection, as well as, from widespread use of advanced treatment processes. Another promising strategy to reduce contamination would be the design and use of less recalcitrant organic chemicals, such as pharmaceuticals and synthetic hormones that are readily (bio)degradable (Daughton and Ruhoy, 2011; Leder et al., 2015).

2.6. Nutrient reuse in non-food biomass production may not lead to circular nutrient flows

Once recovered, human excreta-derived nutrients can be used in both food and non-food biomass production. Recycling of human excreta-derived nutrients to the production of non-food biomass – for example, in forestry (Marron, 2015) and biofuel production (Canter et al., 2015) or on green roofs and sports fields – represents a nutrient loss from food production, at least at shorter time scales. In other words, in such a scenario there is a risk that nutrient recovery and reuse simply substitutes two linear pathways (fertilizer to food production to nutrient dissipation, and fertilizer to non-food production to nutrient dissipation) with one longer one (fertilizer to food production to non-food production to nutrient dissipation). This means that human excreta-derived nutrients may still become dispersed into the environment despite initial recovery and reuse in non-food biomass production. From a nutrient circularity perspective, it is important that nutrients in food products can find their way back to food products. In this regard, reframing highlights the importance of considering whether nutrient recirculation from human excreta via the production of non-food products to food production increases or reduces the contaminant load potentially entering food production when recirculating nutrient-rich products.

3. Conclusions

With the present paper, we echo calls for major transdisciplinary efforts in research, policy, and practice to develop, assess, and implement alternative human excreta management practices. This paper brings attention to the fact that the framing of an issue impacts how the problem is perceived, as well as, the weighting of inevitable trade-offs. We highlight that if human excreta management is framed as part of food and farming systems, several aspects call for more attention, if we are to guide human excreta management towards long-term soil, food, and nutrient security:

- Ensuring extensive nutrient recovery.
- A broader perspective on nutrient recirculation than the present focus on phosphorus and nitrogen.
- Acknowledgement of diverse farming systems that are potential recipients of nutrient-rich products.
- Ensuring that recovered products are compatible with farming systems that are conducive to long-term soil and ecosystem health.
- Development and use of less recalcitrant organic chemicals to benefit recirculation solutions that render products that retain organic matter.
- Differentiation of recovery and reuse solutions that re-circulate nutrients to food production and those that do not.

The reframing of human excreta management as part of food and farming systems was chosen because of the double challenge of urbanization and providing food for a growing population. There are of course other possible ways to frame human excreta management that we acknowledge and respect. What is important is a well-informed dialogue on how different frames of human excreta management in a global and various local contexts impact the outcome, including considerations of social acceptance, technology availability, or economic conditions that were not touched upon in this paper. A constructive dialogue on how human excreta management can best support future agricultural production would benefit from a consolidation of existing evidence on relevant aspects of human excreta management under different frames. Irrespective of the chosen frame, food and agriculture are inevitably linked to human excreta management.

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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.

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