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OPINION

Recovering nutrients from urine – A golden opportunity for sustainable fertiliser production

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Societal Impact Statement

Agricultural industrialisation has led to levels of nutrients in the environment that are well above safe operating limits, yet fertiliser use is necessary to feed a growing population. The recovery of nutrients from human urine in large, developed cities may offset some of the ecological and economic impacts associated with fertiliser production, as well as lessen environmental impacts associated with wastewater. Achieving a circular economy of nutrients faces several challenges, many of which require transdisciplinary solutions. Here we summarise some of the key challenges and highlight potential solutions at all stages from collection at the source to application to plants.

Summary

The utilisation of nitrogen (N) and phosphorus (P) in agriculture has surpassed the safe-operating thresholds for biogeochemical cycles, necessitating the adoption of more efficient nutrient management strategies to restore this balance. The predominant source of N and P supplementation globally stems from the application of synthetic fertilisers. This study explores the potential of nutrient recovery and recycling from human urine as a viable alternative at sub-global and regional levels. Such an approach could significantly reduce energy consumption associated with fertiliser production and transportation, as well as the demand for precursor materials. Additionally, it would mitigate the risk of eutrophication resulting from the release of excess N and P into the environment via untreated or inadequately treated wastewater. By integrating waste material utilisation within the nexus of social and ecological systems, this strategy may enhance socio-ecological resilience, particularly in urban areas. Here, economies of scale could facilitate the successful implementation of urine diversion and conversion initiatives, offering a sustainable solution for nutrient management in densely populated regions.

KEYWORDS

Agricultural sustainability, nutrient management, Planetary boundaries, resource recycling, urine diversion

1 | INTRODUCTION

The planetary boundary framework (Rockström et al., 2009) aims to define safe operating spaces for humanity whilst maintaining resilient Earth systems. Five of the nine proposed planetary boundaries are currently considered to be outside and exceeding safe operating space (Persson et al., 2022). Of those five boundaries, the biochemical flows of nitrogen (N) and phosphorus (P) are well in excess of safe operating limits, and this is generally associated with agricultural industrialistion (Yahaya et al., 2023). It is also clear that whilst global boundaries operate across large geospatial scales, sub-global and regional boundaries can play a role within Earth systems (Steffen et al., 2015).

The utilisation of human urine at the global and sub-regional scale of large, developed cities may play a role in mitigating and managing the biochemical flows of N and P along with freshwater use, generating social-ecological resilience whilst addressing planetary boundary conditions (Rockström et al., 2009). Disposal of urine in cities requires investment into new and ageing sewer and wastewater treatment infrastructure. Urine is the source of most of the N (80–90%) and P (50–65%) in wastewater, along with potassium (K, 50–80%) and several other nutrients (Friedler et al., 2013; Viskari et al., 2018), but traditional wastewater treatment practices fail to capture these nutrients in reusable forms. This is wasteful, given that these nutrients are no longer available for use on land and that some of these nutrients (e.g., phosphorus) are increasing in scarcity (Dawson & Hilton, 2011).

Estimates indicate that less than 5 kg of nitrogen and 1 kg of phosphorus per person per year could be recovered from domestic wastewater, which is significant given that fertiliser application rates in advanced economies range between 16 and 30 kg of nitrogen and 4 kg of phosphorus per person annually, potentially meeting a substantial portion of agricultural nutrient requirements (Hilton et al., 2020). Lohman et al. (2020) argue that realistic recovery rates may be lower due to market limitations, fertiliser competition and insufficient government incentives, especially in low- and middle-income regions. However, recovered nutrients could still provide a viable alternative to expensive, imported synthetic fertilisers in regions with limited fertiliser access, particularly where nutrient deficiencies hinder agricultural productivity.

The recovery of nitrogen and phosphorus from wastewater has the potential to offset a significant portion of global fertiliser demand. If universal sanitation coverage is achieved by 2030 and technology for nutrient recovery is widely implemented, approximately 15 million metric tonnes of nitrogen and 2.2 million metric tonnes of phosphorus could be recovered annually. This represents 11% of synthetic nitrogen use and 9% of mineral phosphorus fertiliser demand globally projected to 2030 (Trimmer et al., 2017). Whilst global potential is high, nutrient recovery varies widely by country and infrastructure quality. Definitive quantification is difficult with nutrient recovery from newly installed sanitation systems, newly treated wastewater and existing system replacement, making recovery rates context-dependent (Trimmer et al., 2017).

Acting on opportunities for recovering nutrients from urine and incorporating them into fit-for-purpose fertilisers requires a transdisciplinary approach that extends throughout the entire life cycle – from the recovery of nutrients at the source and their processing into suitable and safe fertiliser products, to their later use as fertilisers in food production and other forms of land management – and includes perspectives on economics, energetics, sociology, ecology and agronomy. Here, we address some of the key challenges facing those opportunities.

2 | RECOVERY: SEPARATION, PROCESSING AND SAFETY

Modern urban wastewater treatment involves urine as a component within a much larger water flow processed by centralised sewage treatment plants. Thus, these initially high nutrient concentrations in urine are diluted to such low levels that recovery is no longer feasible without further processing from side streams (e.g., anaerobic digestion of wastewater sludge; Stronach et al., 2012). Urine can, however, be collected separately at source using, for example, urine-diverting toilets or waterless urinals with separate plumbing for urine. These systems require little to no flush water, which simultaneously helps conserve water in water-scarce areas and reduces nutrient loads to the centralised treatment plants, leading to reduced energy consumption and financial costs (Maurer et al., 2003). However, retrofitting a separate urine collection system with an existing sewer network can be cost prohibitive. Source separation approaches need to be considered at the planning phase of new developments while working with regulatory authorities and existing utilities to decentralise wastewater treatment. Urea hydrolysis occurs rapidly in undiluted urine, generating ammonia and bicarbonate, causing a simultaneous pH increase that promotes phosphorus precipitation and ammonia volatilisation (Udert et al., 2003). Therefore, transporting urine over long distances for treatment can lead to issues such as pipe blockages and malodorous gas emissions (Udert et al., 2006), in addition to also being very costly. To overcome these issues, new on-site urine treatment and nutrient recovery systems should be considered.

The key to ensuring urine is a resource is reclaiming N, P and K for *beneficial reuse*. As these nutrients are already present in plant-available forms in urine, the main target of the recovery technologies is to recover the nutrients in more concentrated forms, either as liquids or solids, for more efficient fertiliser transport. Direct urine volume reduction, resulting in the combined recovery of all key nutrients, can be achieved through, e.g., evaporation, membrane technologies (such as forward or reverse osmosis, membrane distillation, or electrodialysis) or microalgae cultivation (Larsen, Gruendl, & Binz, 2021; Larsen, Riechmann, & Udert, 2021). Alternatively, more targeted nutrient recovery can be realised, e.g., through a phase change taking advantage of the properties of the target nutrient. For example, ammonia, which is readily volatile at high pH, can be stripped from the liquid phase and reabsorbed into an acidic solution (Maurer et al., 2003). Phosphorus, on the other hand, can be induced to precipitate, e.g., as struvite or hydroxyapatite by the addition of magnesium or calcium (Udert et al., 2003). Furthermore, nutrient-specific adsorbent materials can be used to fix nutrients onto a solid matrix (Larsen, Riechmann, & Udert, 2021). Many of the established nutrient

recovery methods require a steady supply of chemicals or come with a high energy and maintenance need (Larsen, Riechmann, & Udert, 2021). However, urine itself contains chemical energy that could be recovered together with the nutrients utilising microbes to convert chemical energy into electrical energy that is further used as a driving force for nutrient recovery (Ieropoulos et al., 2012). Generally, utilising biological methods helps reduce the energy demand but adds to the instability of a recovery technique, which might limit the adaptation of such systems, especially at the household level.

While these technical innovations for source separation, collection, treatment and recovery are valuable, a significant additional barrier that remains has a social dimension: people need to be willing to use these systems, and they need to be designed for safe operation, minimising direct physical contact. Effective transition management requires consideration of end-users, in this case, those using urine-collecting toilets. The social and psychological barriers of public acceptance are well-known phenomena for general wastewater reuse (Contzen et al., 2023), though these are underappreciated barriers for urine reuse. There has, however, been some research into overcoming public resistance to urine reuse, for example, one study that found visual communication design to be important, given that uses could not be observed and direct feedback was not possible (Lopes et al., 2012). In that study, the use of signage or labelling of toilet paper with 'Thank you for your pee' resonated well with participants and avoided the development of a mindset where users felt they should be rewarded for their donation. Also important was feedback from those impacted by the technology shift: cleaners, plumbers and maintenance staff. Others have demonstrated that acceptance and willingness to reuse urine are driven by social norms (Simha et al., 2021).

At this point, it may be possible to use urine-derived fertiliser products at small scales, but wider use will require demonstration to regulators of their safety. Of particular concern are potential human health and environmental risks including diverse drug and hormone residues (e.g., anti-inflammatory drugs, analgesics, antibiotics, antiallergic drugs, beta-blockers, anti-depressants and caffeine), pathogens (mainly derived from faecal contamination (Schönning et al., 2002) and other potential toxins that could biomagnify in the food chain and be found in urine (e.g., per-and polyfluoroalkyl substances) (Worley et al., 2017). Studies have demonstrated that these risks can be reduced during processing of urine using, e.g., low-temperature direct contact membrane distillation processes to remove odours and pathogens (Volpin et al., 2020), and techniques such as granular activated carbon, biochar/H_2O_2 combinations, UV/H_2O_2 combinations, nano-filtration membranes, or biodegradation and photolysis with algae growth to eliminate drug residues in urine (Almuntashiri et al., 2021). Further studies may be required to gain regulatory and social approvals.

3 | RECOVERY: ECONOMICS AND ENERGETICS

The economic value of nutrient recovery varies globally, with estimates suggesting that nitrogen recovery alone could contribute between US$29 million and $550 million annually in low- and middle-income economies, but with viability remaining highly context-dependent (Lohman et al., 2020). Recovered nutrients can be cost-competitive with synthetic fertilisers, particularly where transport and processing costs are minimised (Hilton et al., 2020). Integrating wastewater treatment with nutrient recovery may offset some costs through lower wastewater treatment expenses (Trimmer et al., 2017); however, in markets where synthetic fertilisers receive government subsidies, nutrient recovery struggles to compete without policy interventions or financial support (Segrè Cohen et al., 2020).

The economic feasibility of nutrient recovery varies depending on the recovery technology and regional context. For example, in Nairobi, Kenya, nitrogen recovery through ion exchange from urine was found to be 40% cheaper than untreated wastewater disposal, with ammonium sulphate fertiliser produced at a lower cost than conventional fertilisers (Tarpeh et al., 2018). Similar trends were observed in Uganda, where sanitation-linked nutrient recovery models demonstrated potential profitability when pricing aligned with or undercut synthetic fertiliser costs (Lohman et al., 2020). However, nutrient recovery facilities in low- and middle-income nations require significant capital investment, making their financial viability dependent on long-term returns and supportive policy frameworks (Hilton et al., 2020).

Despite these challenges, nutrient recovery provides additional economic and environmental benefits. The potential for avoided environmental costs, such as reduced eutrophication and lower greenhouse gas emissions, may justify investment in recovery technologies (Hilton et al., 2020). Moreover, decentralised nutrient recovery systems offer economic opportunities by reducing reliance on imported fertilisers, creating local employment and enhancing food security (Trimmer et al., 2017). However, the economic sustainability of nutrient recovery systems depends on scalability, efficient transport logistics and supportive policies. Without government incentives or market-driven demand, nutrient recovery remains economically marginal when compared to established synthetic fertiliser industries (Boyer & Saetta, 2019).

Studies consistently report a 26–41% reduction in energy consumption for urine-derived fertilisers compared to synthetic alternatives, primarily due to the elimination of energy-intensive nitrogen fixation and resource mining (Hilton et al., 2020; Larsen, Riechmann, & Udert, 2021). Nitrogen fertilisers, particularly those produced via the Haber-Bosch process, require 1–2% of the global energy supply due to the energy-intensive nature of ammonia synthesis from atmospheric nitrogen (Menegat et al., 2022). Phosphate fertiliser production further contributes to environmental impacts through mining and chemical processing, leading to substantial energy consumption and GHG emissions (Jenssen & Kongshaug, 2003). In comparison, urine diversion systems capture nutrients directly from human excreta, eliminating the need for mining and chemical synthesis, resulting in significant energy and environmental savings. This energy efficiency translates to a 29–47% reduction in greenhouse gas emissions, as urine-derived fertilisers avoid the carbon-intensive chemical synthesis processes characteristic of conventional fertilisers (Schreiber et al., 2021). Urine diversion systems may also contribute to lower

freshwater usage and reduced environmental impacts associated with synthetic fertiliser production (Hilton et al., 2020), which may increase in importance as the climate continues to warm and drought intensifies.

The energy requirements for urine-derived fertilisers, however, are context-dependent and influenced by production methods, geographic locations and technological choices. Urine concentration methods, particularly those utilising Reverse Osmosis, are electricity-dependent but can achieve greater energy efficiency when powered by renewable energy sources, as was observed in a Life Cycle Analysis comparing across three US states that differed in the contribution to renewables to their electricity grids (Hilton et al., 2020). In contrast, struvite precipitation and ammonium sulphate production require less energy but involve chemical inputs, increasing the total energy cost because of the requirement to produce and transport those inputs (Hilton et al., 2020). The choice of technology and the energy grid composition significantly affect energy savings, with regions reliant on renewable energy experiencing enhanced efficiency compared to areas dependent on fossil-fuel-based power (Garrido-Baserba et al., 2024).

4 | TRANSPORT: EFFICIENCY AND LOGISTICS

While the environmental benefits and energy savings of urine-derived fertilisers are evident, their energy efficiency is highly dependent on transport logistics and local energy infrastructure (Badeti et al., 2021). Despite lower production energy requirements, transportation energy costs for urine-derived fertilisers can be up to 3.5 times higher than for synthetic fertilisers due to their higher volume and water content, necessitating more frequent and less efficient transport logistics (Badeti et al., 2021; Hilton et al., 2020). In addition, this logistical challenge underscores the importance of localised production and distribution systems to maintain the overall energy efficiency of urine-derived fertilisers.

The feasibility of transporting recovered nutrients is constrained by factors such as distance to end-users, nutrient concentration, transport costs and infrastructure availability. There is a mismatch between urban wastewater nutrient recovery sources and rural agricultural demand, a significant barrier to large-scale nutrient recycling (Trimmer & Guest, 2018). In regions where urban centres are geographically distant from farmland, such as North America, South America and Oceania, the transportation of bulk, water-rich nutrient recovery products is often cost-prohibitive unless coupled with a processing technology that enhances nutrient concentration (Metson et al., 2020). A phosphorus recovery mapping study in the United States highlighted that certain wastewater treatment plants are well-positioned to supply agricultural phosphorus needs, minimising transport distances (Ruffatto et al., 2022). Spatial analyses indicate that in some cases, recovered nutrients can meet a significant fraction of agricultural needs on surrounding land, with studies showing that strategic placement of recovery facilities can supply up to 91% of phosphorus and 44% of nitrogen demands in optimised systems (Metson et al., 2020; Trimmer & Guest, 2018). However, transport inefficiencies and logistical constraints remain key challenges in maximising nutrient recovery potential (Echevarria et al., 2021).

Addressing the challenges associated with nutrient transport logistics requires a combination of technological, policy and spatial optimisation approaches. Developing regional-scale nutrient processing hubs could assist with agricultural demand, reducing transport distances and costs (Trimmer, 2019). However, in cases where wastewater treatment facilities are poorly co-located with agricultural lands, long-distance transport remains an economic and logistical challenge. Policies supporting integrated nutrient recovery within urban sanitation systems could enhance wastewater-sourced fertiliser economic and environmental feasibility (Echevarria et al., 2021). Advances in mapping tools and spatial modelling may further facilitate the optimisation of nutrient transport networks, ensuring that recovered nutrients are competitively positioned against synthetic fertilisers (Hilton et al., 2020). As stated above, the energy requirements and environmental impacts of urine-derived fertilisers are generally lower than those of synthetic fertilisers, particularly when localised production and renewable energy sources are utilised. By prioritising logistical efficiency and strategic infrastructure placement, wastewater-derived nutrients could play a critical role in sustainable agriculture and the transition towards a circular economy. However, to fully realise these benefits, transport logistics must be optimised, and policy incentives may be necessary to enhance adoption and economic viability.

5 | END-USE: APPLICATION, EVALUATION AND ACCEPTANCE

Humans have been using urine as fertiliser long before the invention of synthetic fertilisers. There has, however, been limited work done on the assessment of its agronomic effectiveness relative to commonly used synthetic fertilisers and organic amendments, and on optimising field application rates and timing of application for specific crops and soil types (Mnkeni et al., 2008), both of which are necessary to maximise benefits to farmers. There is also a need to develop appropriate application techniques (e.g., shallow soil incorporation, deep placement, subsurface banding) and equipment to ensure nutrient-use efficiency is maximised and the risk of environmental losses (e.g., through gaseous evolution or runoff) is minimised. Compared with synthetic fertilisers, urine-derived fertilisers can be as effective in stimulating plant growth and crop yield. Additionally, they may contain lower levels of heavy metals (Hilton et al., 2020) and are typically free of pathogens (Simha et al., 2021). Hence, recovery of urine for agriculture use has the potential to reduce the reliance on synthetic fertilisers. Urine is also a locally and constantly available resource as compared to synthetic fertilisers (Mbowa & Siraje, 2020), although this could create new challenges associated with storage during times when plant nutrient demands are low. Research targeted at this, as well as developing best management practices for agricultural use of urine, will ensure nutrient use efficiency is maximised and any potential impact on human health or the environment is minimised.

The fertiliser efficiency of source-separated urine was studied in glasshouse and field-scale experiments in many countries around the world and on different crops such as barley, sorghum, maize, a range of vegetables and ryegrass (Andersson, 2015; Martin et al., 2021; Mchunu et al., 2018; Rumeau et al., 2023). In all investigated cases, the application of urine as a nutrient source resulted in a similar or better plant growth, close (~90%) to that of ammonium-nitrate fertiliser and equal to that of a standard P fertiliser. All these studies have shown that human urine is a fertiliser that can be effectively used for crop nutrition while delivering satisfactory agronomic performance and nutrient-use efficiency when best management practices are followed.

Some environmental risks are a concern, especially N losses, through the processes of volatilisation, denitrification, leaching and runoff (which also applies to P). High application rates of urine-based fertilisers to vegetables and arable crops may cause phytotoxicity due to the accumulation of sodium or leaf scorch, which can inhibit plant growth (Mbowa & Siraje, 2020). The optimum urine application rate that considers nutrient availability and release characteristics in relation to crop uptake and soil type, and possible salinity effects needs to be studied, as does the need for supplemental nutrition when the nutrient ratios present in urine-derived fertiliser products do not align with the nutrient requirements of the crop. Non-concentrated urine may be applied with a slurry applicator. Liquid concentrated urine can be applied with a sprayer equipped for application of liquid fertilisers, side-dressed, or using a slurry spreader, depending on the operating conditions, crop type and crop stage and the target rate. Shallow injection into the soil is preferable to surface application to reduce the risk of N losses by volatilisation (Pullen et al., 2004). Dehydrated products and struvite are more similar to typical synthetic fertilisers and may be applied with the same type of farm equipment if they are transformed into an adapted form (e.g., granular). However, complete fertilisation with non-concentrated urine in an intensive cropping system would require approximately 30 to 250 more quantity of material than a standard fertiliser, which can lead to a significant increase in time, labour and energy involved in its field application, and increased risk of soil compaction (Martin et al., 2021).

Despite the potential for nutrients recovered from urine to be adopted into cropping systems, challenges remain for wide-scale uptake of this technology. There is still a perception that public acceptance of using urine-based fertilisers in cropping systems is limited, due to concerns about health risks, cultural norms, and taboos, as well as other challenges such as restricted information, availability, collection, transportation and storage (Andersson, 2015). This is despite evidence from surveys suggesting a high and growing level of positive attitudes to consuming food produced using nutrients from urine (68%) (Simha et al., 2021). Furthermore, a significant proportion of global agricultural production is concentrated in large countries with low population densities (e.g., Russia, Australia) (Deininger & Byerlee, 2012), and it is unlikely that the recovery of nutrients from urine produced in urban centres in those countries would be sufficient to meet nutritional requirements associated with agriculture in rural areas (Wielemaker et al., 2018). In those cases, those nutrients may be more valuable for use in urban and peri-urban environments including parklands, urban greening initiatives, home gardens and small-scale farming, which would also serve to reduce logistical barriers associated with transport. The viability of urine reuse within a circular economy context also requires further understanding of the interactions between supply, demand and economic factors (Fein-Cole et al., 2024; Nguyen et al., 2024).

6 | CONCLUSIONS

The utilisation of nitrogen (N) and phosphorus (P) in agricultural production is understood to have breached the planetary boundaries of a safe-operating space for biogeochemical flows. In order to achieve a return to the "safe operating space" for humanity, consideration should be given to more efficient nutrient utilisation approaches. The global activation of N and P is dominated by synthetic fertiliser utilisation, and the potential to recoup or recycle these nutrients from human urine may allow for sub-global and regional scales. This may serve important functions to reduce the amount of energy required for fertiliser production and transportation, as well as precursor material demand. It will also reduce eutrophication caused by excess N and P in wastewater accidentally released into the environment or wastewater released via outfalls following lower levels of treatment. Working within the nexus of the social and ecological systems to better utilise waste materials may provide greater social-ecological resilience with a focus on cities and populated regions where urine diversion and conversion strategies may succeed through simple economies of scale.

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CONFLICT OF INTEREST STATEMENT

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

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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