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

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ABSTRACT: The utilization 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 fertilizers. 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 fertilizer 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 utilization 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; Planetary boundaries; nutrient management; resource recycling; urine diversion

The planetary boundary framework [1] aims to define safe operating spaces for humanity whilst maintaining resilient Earth systems. Five of the nine proposed planetary boundaries are currently considered as being outside and exceeding safe operating space [2]. 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 industrialization [3]. 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 [4].

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 [1]. Disposal of this 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 [5,6], 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 are increasing in scarcity [7]. Indeed, the urine produced by an average individual (500 L per year [8]) contains the N and P required to produce the amount of grains they consume in a year (250 kg [9]).

Acting on opportunities for recovering nutrients from urine and incorporating them into fit-for-purpose fertilisers requires a transdisciplinary approach that extends across both ends of the system: 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. Here, we address some of the key challenges facing those opportunities.

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. 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 [10]. 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 whilst 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 [11]. Therefore, transporting urine over long distances for treatment can lead to issues such as pipe blockages and malodorous gas emissions [12], 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 [13]. 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 [10]. Phosphorus, on the other hand, can be induced to precipitate, e.g., as struvite or hydroxyapatite by the addition of magnesium or calcium [11]. Furthermore, nutrient-specific adsorbent materials can be used to fix nutrients onto a solid matrix [13]. Many of the established nutrient recovery methods require a steady supply of chemicals or come with a high energy and maintenance need [13]. 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 [14]. 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 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 [15], though these are underappreciated barriers for urine reuse. There has, however, been some research into overcoming public acceptance of 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 [16]. 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 is driven by social norms [17].

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 fecal contamination [18], and other potential toxins that could biomagnify in the food chain and be found in urine (e.g., per-and polyfluoroalkyl substances [19]). 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 odors and pathogens [20], 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 [21]. Further studies may be required to gain regulatory approvals.

End-use: Application, Evaluation and Acceptance: Humans have been using urine as fertiliser long before the invention of chemical fertilisers. There has, however, been limited work done on the assessment of its agronomic effectiveness relative to commonly used mineral fertilisers and organic amendments, and on optimising field application rates and timing of application for specific crops and soil types [22]. 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 [23] and are typically free of pathogens [24].

Hence, recovery of urine for agriculture use has the potential to reduce the reliance on mineral fertilisers. Urine is also a locally and constantly available resource as compared to inorganic fertilisers [25]. Research targeted at developing best management practices for agricultural use of urine will ensure nutrient use efficiency is maximized and any potential impact on human health or the environment is minimized.

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, range of vegetables and ryegrass [26-29]. In all investigated cases 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. According to all these studies, human urine is a fertiliser that can be used in crop cultivation systems and can deliver good agricultural results.

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 accumulation of sodium or leaf scorch, which can inhibit plant growth [25]. The optimum urine application rate that considers nutrient availability and release characteristics in relation to crop uptake, and possible salinity effects need to be studied. 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 volatilization [30]. Dehydrated products and struvite are more similar to typical mineral 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 [27].

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 [28]. This is despite evidence from surveys suggesting a high and growing level of positive attitudes to using urine as fertiliser (68% [24]). Further, a lot of agricultural production occurs in large countries with low population densities (e.g., Russia, Australia [31]), 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 [32]. 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 [33].

Conclusions: The utilization of N and P in agricultural activities 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 utilization approaches. The global activation of N and P is dominated by synthetic fertiliser utilization and the potential to recoup/recycle these nutrients from human urine may allow for sub-global and regional scales. This may serve important functions to reduce energy use requirements 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.

Declaration of competing interest

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

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