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Ecological sanitation and nutrient recovery from human urine: how far have we come? A review

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ABSTRACT

To address the shortcomings of modern wastewater treatment, Ecological Sanitation (EcoSan) has been advocated as a sustainable approach to promote closed–loop flows of resources and nutrients from sanitation to agriculture. In this study, we discuss the rationale behind its conception and provide a state–of–the–art review on the subject. Through an exhaustive literature analysis of EcoSan systems, its historical developments and programs implemented worldwide we (i) validate the potential applicability and feasibility of decentralized, source–based sanitation and (ii) depict fundamental problems in EcoSan systems design that have stalled its adoption and proliferation. Specifically, we focus on urine diversion to demonstrate its potential to elegantly separate, collect and concentrate products that we require (nutrients) and those that we wish to regulate (pathogens and micropollutants). Since recent research efforts have been devoted to the technological recovery of nutrients from human urine, we believe that we are witnessing a paradigm shift within a paradigm shift as it represents a change in emphasis from ‘split–stream collection and reuse’ to ‘split–stream collection, resource recovery and safe reuse’. Our analysis of various nutrient recovery technologies for human urine indicates that provisioning of urine–diverting toilets tends to reduce sanitary risks; however, to contain and completely eliminate these risks continued research effort is needed to envision and implement integrated technological pathways that ensure simultaneous nutrient recovery, pathogen inactivation and reduction of pharmaceuticals and active substances.

1. Introduction

For a long time, the international agenda has neglected the aspects of sanitation and health in its push for (sustainable) development. It is not surprising to note that, 36% of the global population still lacks access to improved sanitation facilities [1,2]. At the other end of this spectrum lies the issue of clean drinking water as nearly 1 billion people still depend upon unimproved sources to satisfy their daily needs [3]. The continued failure to address these problems has significantly altered the global health burdens, effects of which have been well recognised and documented [4-6]. Certainly, providing and improving access to sanitation, a precondition for human development is vital; however, the problems surrounding sanitation extend far beyond its mere provisioning which has otherwise been the focus of sanitation outreach programs.

The design and operation of conventional Wastewater Treatment Plants (WWTPs) is grounded in a philosophy that considers human excreta as ‘waste’ that require treatment and removal from the built environment. The primary objectives of these systems are to (i) ensure minimal exposure of humans to such wastes by creating an effective barrier (toilets) and (ii) facilitate appropriate disposal of these wastes through end–of–pipe technologies [7]. When it leaves the human body, excreta, despite being pathogenic is a point source of potential disease transmission. It is through the use of a sewage network that transports wastes to centralised WWTPs [8] that has opened up new pathways and magnified the scale of contamination ‘beyond the toilet’. In addition to the linearity in flow of (waste) resources these systems promote, essential drawbacks of ‘modern’ WWTPs also include poor financial sustainability, high energy requirements and water intensity, sensitivity to discharge loads and inadequate final treatment which in turn becomes a vector of diseases [9]. The ultimate disposal of the treated wastes in landfills and in water bodies only adds to the already high environmental burden and externalities [1,7].

Hence, linearity, methodological reductionism and sequential uniformity appear to be characteristic attributes of the conventional approach to socio–economic developmental issues including that of sanitation [10]. It is precisely this cognition that fails to consider humans (and their actions) as being part of a complex, non–linear, dynamic and interconnected system. Today, while we live in an era of high environmental consciousness we also live in times of great uncertainty of the repercussions of our past and present actions [11]. Yet, our current systems attempt to address the problems in sanitation, health, water and agriculture in isolation; most of our on–going efforts in these sectors are geared to seek specificity in the implemented and/or proposed solutions thereby failing to realise any synergistic benefits.

On the other hand, contemporary levels of food production have been aided largely by the continuous application of industrial, fossil fuel–sourced fertilisers [14]. However, the mobilisation of significant amounts of plant–required nutrients for fertiliser production has interfered with the functioning of global biogeochemical cycles. Cordell et al. look towards phosphorous, 90% of which is sourced for food production to depict a likely peak in its global output by 2030 and an accelerated depletion thereafter [15,16]. Two fundamental aspects that shape the present (and future) global food security are: (i) the anticipated rise in global population coupled with higher disposable household incomes in developing countries will increase the demand for quantity and quality of food [12]; and (ii) a likely economic and physical scarcity of natural resource due to limits over its extraction will constrain agricultural production [13]. Hence, ensuring long–term soil fertility to sustain food production in a resource–scarce scenario (declining synthetic fertilizer production) undoubtedly necessitates the envisioning of approaches markedly different than those in place today. To this effect, source–separation, concentration and recirculation of human wastes (urine and faeces) from the built to the natural environment where it can be used as a crop fertilizer has been advocated as a sustainable solution to the issues surrounding the nexus of sanitation, water, heath, and agriculture [17]. Conceptual complexity in line with a circular systems approach and holism could therefore be accomplished *if* agriculture (food security) is introduced into the sanitation–water–health equation.

Hence, in this paper, we provide a state–of–the–art review on ecological sanitation and source–separation of human waste (Fig. 1). During the review, the broader question whose answer we seek is whether we can indeed create sanitation systems that safely recycle value–added, nutrient–rich products between urban and rural areas, in quantities that ease their application, and in forms that are plant–available.

2. Human 'wastes' or 'resources': Characterizing the potential

The physical and chemical composition of various fractions of human excreta have been the focus of several thematic areas of research including waste treatment and management, nutrition, physiology and medicine, waste reclamation for space travel, etc. Tables 1 and 2 enlist the various properties and nutrient concentrations for human urine and faeces. The quantity, physical characteristics and chemical composition of the excreta fractions are likely to be influenced by factors including age, gender, diet, protein, fibre and calorie intake [17], geographical location, income levels and socio–cultural factors [18]. Wolgast [19] reported that an average individual excretes around 500 kg of urine and 50 kg of faeces (dry matter content of 20%) each year with total nutrient composition of excreta (faeces + urine) as follows; 5.7 kg N, 0.6 kg P and 1.2 kg K. However, 90% of the *tot*–N, 60–65% of *tot*–P and 50–80% of K are partitioned by the human body and excreted in the urine. Elsewhere, Jönsson et al. [20] estimated that the average annual per capita urine production was 500 L. On a wet weight basis, Faechem et al. [18] distinguished the faecal production in developing countries (130–520 g person^{-1} d^{-1}) and, North America and Europe (100–200 g person^{-1} d^{-1}). More recently, in a survey of three case study locations across South Thailand, Schouw et al. [21] observed the per capita daily production rates for urine and faeces to be 0.6–1.2 L and 120–400 g, respectively. Good agreement of the data was seen with a comparable Vietnamese case study where Polprasert et al. [22] estimated the production of urine as 0.82–1.2 kg person^{-1}d^{-1} and faeces as 130–140 g person^{-1} d^{-1}. Further, Schouw et al. [21] also found that the per capita daily nutrient loading of the excreta was 7.6–7.9 g N, 1.6–1.7 g P, 1.8–2.7 g K, and 1.0–1.1 g S.

In terms of its chemical composition and fertilizing ability, human urine is a nitrogen–rich aqueous solution wherein, urea contributes towards 75–90% of the tot–N in urine [23,24]. Important to note is the fact that 97% of the total volume of human urine is comprised of water [25]. Although the P/N and K/N ratios in urine are relatively lower in comparison with synthetic fertilizers, the ability of the phosphates and potassium compounds to be readily water soluble (and hence, plant–available) upon application by virtue of their ionic form counters this to some extent [26].

Karak and Bhattacharya [27], through a review of research concerning the elemental composition of urine illustrate that its heavy metal concentration is low. Vinnerås and Jönsson [28] also remark, since our consumption of heavy metals (in food) itself is low, our bodies excrete low concentrations of these substances; in fact, the major contribution of heavy metals to the environment comes not from human excreta but effluent flows such as dyes, chemicals, ore processing, etc. In contrast, the use of synthetic (mineral) fertilizers has been well correlated with the contamination of soils and water resulting in considerably high concentrations of heavy metals in crops and livestock feed [29-31]. Since particularly high levels of Cd, Pb, Cu, Co, Mn and Zn having been reported, researchers have called for precautionary measures and regulations against the misuse of mineral fertilizers in lieu of their potential toxicity [29]. In addition, Aoun et al. [32] have recently illustrated that the processing and manufacturing of phosphate fertilizers is also a major contributor to locally elevated levels of heavy metal concentrations.

3. An ecological sanitation approach

Ecological Sanitation (EcoSan) is a concept formulated through an approach that integrates various schools of thought such as circular economy, general systems theory, industrial ecology, biomimicry and life–cycle thinking [7]. It claims to address the aforementioned shortcomings in our systems of sanitation and food production by initiating a paradigm shift in the way we perceive and manage human wastes [33]. EcoSan seeks to blur the comprehension of two human constructs, 'resources' and 'wastes' by contending that, human excreta are in fact resources of a natural cycle that circulates biological nutrients. By making a case for resource recycling through the promotion and reuse of human excreta as fertilizers, EcoSan demonstrates a closed loop methodology for reintroducing resources and nutrients from wastewater back into agriculture rather than letting them diffuse into freshwater bodies which has otherwise been the norm today. In effect, it seeks to advocate a philosophy of handling and using materials that have been, until now, assumed to be wastes that need to be discarded, treated and/or disposed. EcoSan's guiding principles favour the creation of tailored, location and context–specific sanitation solutions; this is guided by the understanding that technologies are only end–points or a 'means to an end' to achieve the broader goal of creating improved sanitation services. Hence, EcoSan does not encourage the adoption of any specific sanitation technology [9].

3.1. EcoSan and source separation of wastes

The working strategy and distinguishing feature in EcoSan are the concept of source separation, split–stream collection and individual treatment of various wastewater fractions, viz. urine (yellowwater), faecal matter (brownwater), blackwater (urine + faeces) and greywater (excreta–free household wastewater). To allow the separation of these streams at source, i.e., households, the technological solution employed is 'urine diversion' through the use of a diverting toilet [34]. These toilets take advantage of human physiology which separately excretes faeces and urine; the toilets are engineered so as to facilitate the collection of urine in a front end bowl and faeces in the rear–ended bowl [35,36]. These toilets are available in various modules wherein, both/either/none of the two receptacles of the diverting bowl can or cannot be flushed with water and based on this functionality, a urine diverting toilet (UDT) may also be categorized as a Urine Diversion Dry Toilet (UDDT).

The rationale for source–separation seems obvious, at least in the present times as there is growing recognition that human urine, which contribute to less than 1% of the total wastewater volumetric flow accounts for more than 80% of the *tot*–N and more than half of its *tot*–P and *tot*–K [28,33,37]. Besides, collection of the dry faeces that contains most of the pathogens separate from the urine reduces the risk of potential transmission of water–borne diseases [4,5]. By elegantly preventing the mixing of these waste fractions diverting toilets, in essence, allow concentration of both nutrients as well as pathogens *at source*.

Drawing upon the concept of 'waste design' proposed by Henze [38], source separation can be considered a waste segregation step as it has the ability to render better control over various process parameters that influence the efficiency of wastewater treatment. By modelling a process that integrates urine diversion with conventional WWTPs, Wilsenach and van Loosdrecht [39] demonstrate that, by reducing 50% of the urine volumetric flow to a conventional WWTP reduces the N–loads for treatment by ~2–3 g m^{-3}; at higher rates of diversion, the WWTP could in fact achieve an energy surplus. Similarly, Ng et al. [40] have shown that reducing the discharge of urine by utilizing lesser volumes of flush water reduces environmental externalities and is an economically favourable option for ensuring long–term water security in Singapore. Comparing the energy turnover, Tidåker et al. [41] in their modelling of a local Swedish recycling and wastewater treatment scenario that included both capital expenditure and operating costs depicted that, urine separating systems use the least amount of primary energy. Recently, Gao et al. [42] through an input–output analysis of five different toilets design installations in rural China concluded that UDTs outperformed conventional toilets both economically as well as in overall environmental performance. Similar findings were also reported by Lam et al. [43] in their life cycle simulations for rural sanitation systems in Tianjin, North China.

The applicability and feasibility of diverting toilets as an alternative to conventional sanitation systems seems to be well established. This is evident through the number of installations of diverting toilets across the world; this includes the sale of over 300,000 UDTs by the Sweden–based company, Separett® AB [44], the large–scale rural and peri–urban sanitation programme in Durban, South Africa which encompasses 75,000 UDDTs serving nearly 450,000 inhabitants [45], or the Community–Led Total Sanitation WASH program implemented in Liberia which provided access to improved sanitation for over 100,000 people [46], as well as UDDT installation of around 900 in Bolivia [47], approximately 1000 each in Kenya, Burkina Faso and Uganda [48], 575 in Sofala province, Mozambique, close to 800 double vault bench–type UDDTs built near Lima by Rotaria del Perú® SAC [49], and the 500 pit latrines at the Farchana refugee camp in Chad [48].

Furthermore, based on suitability and adaptability of various options for ecological sanitation, for a given context, location and set of socio–economic and cultural circumstances, recommendations have been already been put forward that allow the identification of an appropriate sanitation technology. Detailed procedures are now available for the design, construction, installation and use of various parts of the diverting toilet and the overall system. Besides, guidelines on safe source–separation, storage and re–use have already been published [20,50–59].

3.2. Implementing, adopting and validating EcoSan systems and programmes

When looking towards the implementation of EcoSan programmes, it is prudent to draw a distinction between studies that address field/on–site application of the technology itself and the studies that deal with recording user perceptions, attitudes, experiences and willingness to adopt these new systems that we advocate. Through a technological perspective, several investigations have dealt with the application of source–separated wastes as fertilizers, at various scales of implementation [60–68]. Based on the results of these studies some broad observations can be drawn: (i) conditioning the soil with human excreta enhances crop productivity when compared to the control (no treatment); (ii) ammonia losses from urine depend on the manner in which it is spread and introduced in the soil and can be minimized through practices such as harrowing [69,70]; (iii) nutrients present in excreta are either plant available or are become plant–available over time as compounds with low solubility such as inorganic P (> 95% of *tot*–P) [71] (iii) yields of excreta–fertilised plants are similar to that obtained when mineral fertilisers are added in the same ratio; however, the yield is sensitive to N–loading from urine which is a fast–acting liquid fertilizer [20]; and (iv) the attraction towards urine largely stems from aspects such as low capital investments, ease of infrastructural retrofitting, demonstrated increase in crop yields, the promise of an essentially ‘free’ and sustainable supply (‘ubiquity’) of nutrients and simultaneous improvement of sanitary hygiene through use of diverting toilets [72].

Ever since its conception in the early 1990s, EcoSan and its underlying principles have been implemented as pilot projects in diverse geographical settings [48,73–81]. These projects have contributed significantly towards the development of alternative sanitation systems while reiterating the underlying assumption of the geographical applicability of EcoSan. These studies have spanned across industrialised countries like Germany [82], Sweden [81], Netherlands [83] and Denmark [76], emerging markets like India [7], China

[84] and South Africa [85], N–11 countries such as the Philippines [86], Indonesia [77], Turkey [78] and Pakistan [87] as well as developing/under–developed nations including Nepal [75], Malawi [88], Burkina Faso, Kenya, Tanzania and Mozambique [48]. The problems encountered and highlighted when implementing and using these systems have been discussed in Section 3.3.

On the contrary, through a socio–economic and cultural lens, studies have been conducted to record and analyze the user perspective to EcoSan. The end application of EcoSan systems rests with users who need to be convinced to shift away from their current practices and adopt these new systems of sanitation, fertilization and food production; hence, they are the ultimate determinants of its proliferation potential and subsequently affect the timing, nature and extent of the change in paradigm that EcoSan systems seek to effect. However, sociological investigations on the subject have been relatively few as also pointed out by Judit Leinert in her recent review where she states, '*I know of four questionnaire surveys addressed to the general public and four to the farmers that elicited their acceptance of reusing human urine in agriculture*' [89]. A survey on urine separation systems across seven European countries on urine diversion indicated that more than two thirds of the users liked the idea and were satisfied with its performance, and would buy urine–fertilized food [90]. Further, a study analysing the perception of 467 Swiss farmers indicated that 57% liked the idea of using urine–based fertilizers with 42% stating they would be willing to buy such products if manufactured; however, a widely raised concern among the farmers was the concentrations of micropollutants and hormones in the fertilizer [91]. Andersson [72], analysing the attitude of Ugandan farmers reported that the support for urine fertilization was due to its ability to ensure food and economic security given that they have few other options for soil nutrient management; in contrast to the Swiss farmers however, the farmers did not consider risks from pharmaceuticals to be significant. Recently, Ishii and Boyer [92] promoting universities as ‘excellent testbeds’ for studying and introducing urine diversion observed that, 84% of their respondents indicated that they would demand for source separation systems to be installed in their halls of residence; however, this declined significantly when the participants were asked if they would be willing to pay/contribute for it themselves. Similar observations on the attitudes of consumers with respect to willingness to pay have been made earlier by Pahl–Wostl et al. [93]. In contrast, Lamichhane and Babcock [94] reported that more than 60% of their test sample of 132 people from the University of Hawaii indicated their willingness to pay an extra $50 to install a diverting toilet. Other studies on the subject include those of Cordova and Knuth [95] in Mexico, as well those reporting negative user attitudes such as Mugivhisa and Olowoyo [96] in South Africa and Mariwah and Drangert [97] in Ghana where residents accepted that excreta can be used as fertilizers although they themselves were not willing to do so.

At the very least, these studies stand testament to the fact that people are certainly open to the idea of source separation and nutrient recycling and perhaps, it would be erroneous to overestimate the extent of the phobia against the reuse of excreta. Besides, these studies continue to provide valuable insights that reduce the risk of potential failure and allow alternative sanitation systems to be tailored to user requirements such as the demand for grainy urine–based fertilizer by Swiss farmers [91] or better system aesthetics in Mexico [95], or the identification of problems like pipe blockages and issues with user–compliance such as improper flushing habits [90]. The joint–development of technologies by the research sector, manufacturer and user thus appears to be vital in ensuring the successful adoption of technologies that necessitate significant behaviour modification and adoption of environmentally–sound behaviour.

3.3. *Urine diversion, the gaps and problems*

Source separation and reuse of waste fractions have had to encounter and address several issues and may be not be entirely ecologically–sound as we presume they were. At the outset, we must acknowledge that human urine is a fast–acting liquid fertilizer that requires careful application and regulation, the absence of which, can cause volatilisation of intrinsic ammonia (a greenhouse gas), increase soil conductivity, salinity and pH; poor agro–productivity or in some instances, crop failures [63,64,98]. Hu et al. [99] recently emphasized this by observing that the use of organic liquid fertilizers would ‘most likely lead to increased atmospheric emissions of ammonia resulting in acidification of soil and water.

More importantly, life cycle cross–comparisons with conventional WWTPs [41,100] indicate that significantly large volumes of urine are required to provide a fertilising effect equivalent to synthetic fertilisers. Large volumes necessitate additional investment for urine collection, handling, storage and transportation to farmlands which tends to reduce systemic efficiency and cost savings vis–à–vis conventional systems. A major challenge in closing the sanitation cycle lies in the logistics of connecting farmers (nutrient sinks) with citizens (source of nutrients) that use decentralized (in some cases, semi–decentralized) sanitation systems; in trying to provide the farmers with homogenized and standardized fertilizer products [101] that ensure sustained reproducibility of crop yield enhancements.

In addition, UDTs are connected to tanks that store around 300–500 L of urine. During pipe transport and storage, bacterial urease (urea amidohydrolase) catalyses the hydrolysis of intrinsic urea (Eq. 1). The implications of ureolysis are (i) it completely converts urea into carbon dioxide and ammonia that subsequently volatilises ($pKa = 0.09018 \pm 2729.92\ T^{-1}$) [102]; (ii) it elevates the pH, and reduces the potential reusability of N in post–storage applications; (iii) elevated pH triggers the precipitation of struvite ($MgNH_4PO_4 \cdot 6\,H_2O$) and calcite ($CaCO_3$) which creates blockages in the odour traps and pipelines [103]; and (iv) it results in the physico–chemical and microbial stratification of the urine during storage [104].

$$NH_2(CO)NH_2 + 2H_2O \rightarrow NH_3 + NH_4^+ + HCO_3^- \qquad (\mathbf{1})$$

A further concern in UDTs is cross–faecal contamination of the relative sterile and source–separated urine. Inactivation studies with urine point towards significant pathogenic risk due to the persistence of, among others, faecal sterols, *Enterococcus*, *Escherichia coli, Salmonella*, helminth ova such as *Ascaris*, rotavirus and bacteriophages, [105–108]. In a study that analysed 15 different storage tanks in Sweden and Australia, faecal sterols were found to cross–contaminate 22% of the samples in the upper portion and 37% of the samples from the sludge [109]. Nyberg et al. [108] argue that microbial persistence also extends to the application of excreta in soils which creates further disease transmission pathways. Due to these factors, the WHO [59] recommends that, for production and raw consumption of crops, urine has to be stored for at least 6 months ($T > 20$°C) before application to ensure 'high' level of pathogen inactivation. Besides, the quantification, behaviour and potential negative effects of micro–pollutants and pharmaceutical residues in source–separated human urine are not well understood. In light of this scientific uncertainty, Larsen et al. [37] invoke the 'precautionary principle' over application of fertiliser products from EcoSan systems. Even if we choose to not consider the socio–cultural inhibitions against the use of human excreta which Jewitt [110] observes to be an obvious aspect hindering the spread of EcoSan, there appear to be other fundamental concerns with respect to the technological and system design aspects of EcoSan systems. As the narrative adopted here elucidates, these flaws in system design have stalled the proliferation of nutrient recycling. Nonetheless, EcoSan does provide an efficient way to separate, collect and concentrate products that we require (nutrients) and those that we wish to regulate (pathogens, micropollutants, heavy metals).

4. *Technologies for nutrient recovery: progress, gaps and opportunities*

Over the last decade, the research focus in EcoSan has shifted from studies that validate the potential of human excreta for fertilization to studies that identify and realize the recovery of nutrients and resources from source-separated human excreta. Since we consider EcoSan itself to be an alternative paradigm, this change in devotion of research efforts by the scientific community appears to be a paradigm shift within a paradigm shift as it represents change in emphasis from ‘split–stream collection and reuse’ to ‘split–stream collection, resource recovery and safe reuse’. By simultaneously mapping the chemical/nutrient composition of various potential fertilizer products from eco–sanitation systems against their suitability for production of crops, Winker et al. [107] illustrate how urine is the ‘most promising’ and ‘well investigated’ product from such systems. Hence the focus in this study too will be towards recovery technologies for human urine. Several investigations have reported the development of technologies that can safely harness nutrients from human urine to yield usable end–products [111–119] (Fig. 1).

An approach favoured by many researchers has been struvite ($MgNH_4PO_4 \cdot 6H_2O$) precipitation where significant P and some N as $(NH_4)^+$ has been recovered [103,114,120–123]. However, the process is contingent on external addition of Mg as MgO, $MgSO_4 \cdot 7H_2O$ or $MgCl_2 \cdot 6H_2O$ which elevates the pH, reduces the solubility of $(PO_4)^{3-}$, induces supersaturation and spontaneous precipitation. By controlling the dosage of $MgCl_2 \cdot 6H_2O$ and the pH of urine, it is possible to precipitate either potassium magnesium phosphate or magnesium ammonium phosphate. Complete P recovery can be attained by the precipitating either of these compounds [124]. Nevertheless, as Etter et al. [125] note, the recovery of ammonium through struvite precipitation may be only 5% and other macronutrients may not be recovered; the authors, using the case of study of Nepal also emphasized that the struvite allows harnessing only 13% monetary value of urine as a fertilizer.

Technologies used in water treatment have also found application in nutrient recovery from urine. For instance, Dodd et al. [115] demonstrated the ozonation of hydrolysed urine for nutrient recovery which also allowed depletion of indicator micropollutants. Through adsorption procedures, Ganesapillai et al. [119] recovered urea using coconut shell based activated carbon while Lind et al. [121] used clinoptilolite and wollastonite for nitrogen fixation after struvite precipitation. N recovery through stripping operations has been performed as standalone or with other operations such as absorption, struvite precipitation, evaporation, etc. [112]. Dewatering hydrolysed urine by forward osmosis was demonstrated by Zhang et al. [118] although N recovery from this process is poor. Recently, biological nitrification in combination with alkaline stabilization and distillation as investigated by Udert and Wächter [116] illustrated near complete recovery although process energy requirements were found to be 4–5 times of conventional wastewater treatment. Other advocated technologies studied include volume reduction through freezing–thawing [126] as well as drying [127], ion–exchange with targeted P recovery [117,128] and anaerobic treatment [111].

The analysis of literature on nutrient cycling illustrates that, although these technologies have been influenced by ecological considerations, they demonstrate variable efficiency in recovery of the major nutrients (NPK) from urine. Since many of these processes have been engineered to optimise certain parameters they fail to provide integrated nutrient recovery; in their review of existing technologies, Maurer et al. [112] reiterate this observation. For instance, N removal through struvite precipitation is relatively poor in comparison to the recovered P [121]; persistent pathogen build–up has been recognized in the precipitated struvite in spite of post–separation air drying of the cake [129]. Recently, Ishii and Boyer [130] also stressed the need for continued research on nutrient recovery technologies ‘beyond struvite precipitation’. Besides, in an audit of 12 toilet designs (with and without urine diversion), Starkl et al. [101] observed that, decentralized treatment processes such as anaerobic digestion, dehydration, and composting have proven to be insufficient and invariably necessitate significant user maintenance.

Furthermore, with regards to the concentration of pharmaceuticals and micropollutants, it would be prudent to consider that human urine contains far lesser concentrations of these compounds than wastewater or farm manure and excreta [131]. Moreover, as Rehman et al. [132] observe, the most significant contribution (hence, risk) of active pharmaceuticals to the environment stems from the pharmaceutical industry itself; this is especially true for densely populated developing countries where pharmaceutical production has grown tremendously but not commensurate with efficiency or extent of effluent treatment. Indeed, Larsson et al. [133] demonstrated that 'treated' effluent from a wastewater plant that served 90 (bulk) drug manufacturers in Hyderabad, India contained the 'highest level of pharmaceuticals reported in any effluent' with detected levels of ciprofloxacin (28–31 $mg\,L^{-1}$) exceeding levels of EC_{50} toxicity for bacteria by orders of magnitude. The authors also raised concern of enhanced risk from development of anti–biotic resistance in pathogens as the treatment plants operations involved mixing human sewage with the drug manufacturer's effluents. This only goes to substantiate the case for implementing diversion–based decentralized sanitation systems which at the very least allow localized concentration of pollutants that we wish to target and eliminate. Of course, this also begs the question as to why EcoSan systems must be judged against standards of treatment that current centralized treatment plants themselves do not meet. While not advocating for relaxing regulations for EcoSan systems or setting a lower benchmark, it does point towards factors such as institutional resistance against changes to conventional systems. More importantly, concerns over active substances provide further opportunities for researchers working with EcoSan systems to ensure that post–diversion processes are compliant with regulatory requirements.

Hence, the realization of a closed loop sanitation system that aspires to reutilize human urine hinges considerably over post–urine diversion operations. It is in these steps that there lies an opportunity for substantial value creation (through the processing and production of urine–based fertilisers) as well as risk minimization (through pathogen inactivation and micro–pollutant elimination). While we tend to reduce these risks through the provisioning of (urine–diverting) toilets, for us to contain and eliminate them, continued research effort to envision and implement *integrated nutrient recovery technologies*. To accelerate the proliferation of urine diversion and adoption of decentralized sanitation system, we believe that, it is imperative for us to devise 'integrated' technological pathways for post–urine diversion operations that simultaneously provide near-complete nutrient (NPK) recovery, pathogen elimination and reduction of pharmaceuticals and active substances in line with regulatory requirements.

5. Conclusions

This review pointed out two significant factors that will shape the research in EcoSan systems over the coming years; (i) realization of 'integrated' treatment of post–urine diversion waste fractions as these steps harbour the most potential for value creation and risk minimization; and (ii) addressing issues with pharmaceuticals, pathogens and micro–pollutants in source–separated wastes by identifying and implementing ecologically–sound treatment processes that ensure 'safe reuse' of wastes as fertilisers. Along these lines, we believe that, EcoSan and its non–technology centric guiding principle should be restricted only to the design of the user interface and the choice of the toilet. This stems from the understanding that, although there is need to tailor sanitation systems to a particular set of circumstances and conditions, a specific set of homogenous technological solutions are also required to ensure that we do end up safely closing the loop on sanitation.

Surely, the call and the rationale for changes to the current paradigm of waste management must be incontestable as there seems to be enough evidence to demonstrate that everything is not right with the way we manage human wastes. EcoSan and nutrient recovery technologies are perhaps inevitable changes to the way we perceive, manage and reuse our wastes. The pace and extent of its adoption and implementation however are aspects that remain to be seen.

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Table 1: Physico–chemical properties and nutrient composition of human urine

Parameter	**Value**	**References**
pH	8.9–9.2	[134]
	6.3–6.9	[123]
	5.8–6.4	[135]
	6.5–6.8	[128]
	5.6 ± 0.4	[125]
	8.25–8.55	[136]
	6.2–6.6	[123]
	8.9–8.96	[24]
	5.6–6.8	[121]
	9.0	[137]
	9.2	[65]
	6.2	[103]
	9.0–9.1	[138]
EC	14.4–16.4 mS cm^{-1}	[135]
	22.6 ± 6.3 mS cm^{-1}	[125]
	160 mS cm^{-1}	[139]
	270 mS cm^{-1}	[69]
	13.4–19 mS cm^{-1}	[24]
	47.2 mS cm^{-1}	[65]
COD	7660 ± 4630 mg L^{-1}	[125]
	4–11 g L^{-1}	[140]
	8.5 g person^{-1} d^{-1}	[141]
	3723 g person^{-1} yr^{-1}	[142]
***Tot*–K**	0.76–0.92 g L^{-1}	[134]
	966–1,446 mg L^{-1}	[135]
	0.027–0.036 g person^{-1} d^{-1}	[143]
	1870 ± 976 mg L^{-1}	[125]
	800–1000 mg L^{-1}	[104]
	1.1–1.3 g person^{-1} d^{-1}	[144]
	1.2 g L^{-1}	[69]
	2.4 g person^{-1} d^{-1}	[141]
	0.87–1.15 g L^{-1}	[24]
	0.7–3.3 g L^{-1}	[140]
	2 g L^{-1}	[65]
	0.75–2.61 g L^{-1}	[145]
	300 mg L^{-1}	[57]
	2200 g m^{-3}	[103]
	0.78–2.5 g person^{-1}d^{-1}	[146]
***Tot*–P**	0.24–0.28 g L^{-1}	[134]
	1.8 g L^{-1}	[123]
	0.45–0.71 g person^{-1}d^{-1}	[143]
	150–275 mg L^{-1}	[104]
	0.4 g person^{-1}d^{-1}	[144]
	350 mg L^{-1}	[69]
	0.9 g person^{-1}d^{-1}	[141]
	280–400 mg L^{-1}	[123]
	0.20–0.21 g L^{-1}	[24]

	0.2–3.7 g L^{-1}	[140]
	0.7 g L^{-1}	[65]
PO$_4$–P	388 ± 251 mg L^{-1}	[125]
	0.703 ± 0.142 g L^{-1}	[136]
	2.03 g L^{-1}	[65]
	0.205 g L^{-1}	[57]
	740 g–P m^{-3}	[103]
	0.8–2.5 g L^{-1}	[146]
***Tot*–N**	4.28–4.97 g L^{-1}	[134]
	8 g L^{-1}	[123]
	2.1–3.3 g L^{-1}	[104]
	4.2–4.9 g person^{-1} d^{-1}	[144]
	4 g L^{-1}	[69]
	11–13.9 g L^{-1}	[20]
	11 g person^{-1} d^{-1}	[141]
	1.78–2.61 g L^{-1}	[24]
	1.8–17.5 g L^{-1}	[140]
	12 g L^{-1}	[147]
	8.36 g L^{-1}	[65]
NH$_4^+$–N	333–540 mg L^{-1}	[135]
	150 mg L^{-1}	[128]
	438 ± 207 mg L^{-1}	[125]
	0.765 ± 0.177 g L^{-1}	[136]
	2.0–3.3 g L^{-1}	[104]
	0.12 g L^{-1}	[139]
	480 g–N m^{-3}	[103]
	1.12–1.73 g L^{-1}	[24]
	8.57 g L^{-1}	[65]
NO$_3$–N	0.438 ± 0.071 g L^{-1}	[136]
	45 µg L^{-1}	[24]
	0.01 g L^{-1}	[65]
NH$_3$–N	3.2 ± 0.17 g L^{-1}	[138]
	0.48 g L^{-1}	[57]
	340–530 mg L^{-1}	[123]
NH4$^+$+NH$_3$–N	415 ± 30 mM	[137]
	200–730 mg L^{-1}	[145]
CO(NH$_2$)$_2$	10–35 g person^{-1} d^{-1}	[148]
	4450 ± 1730 mg L^{-1}	[125]
	21.4 g L^{-1}	[141]
	10 g L^{-1}	[149]
	0.27 ± 0.05 mol L^{-1}	[113]
	9.3–23.3 g L^{-1}	[145]
	7700 g–N m^{-3}	[103]
	85% of *Tot*–N	[24]
	75–90% of *Tot*–N	[23]

Table 2: Physico–chemical properties and nutrient composition of human faeces

Parameter	**Value**	**Reference**
pH	7.5	[150]
	8–8.3	[137]
	6.6	[17]
	6.18–6.65	[151]
	6.7–8.4	[152]
	7.0–7.2	[153]
	5.3 ± 0.2	[154]
EC	3.3 mS cm^{-1}	[17]
	60.0 ± 15.0 mmho cm^{-1}	[154]
COD	64.1 g person^{-1} d$^{-1\,*}$	[141]
	37–36 g person^{-1} d^{-1}	[140]
	1668 g person^{-1} d$^{-1\,*}$	[155]
	71 g person^{-1} d^{-1}	[17]
***Tot*–K**	0.8–2.1 g person^{-1} d^{-1}	[156]
	4.936 g kg^{-1}	[157]
	0.9 g person^{-1} d$^{-1\,*}$	[141]
	0.8–1.0 g person^{-1} d^{-1}	[111]
	0.24–1.3 g person^{-1} d^{-1}	[140]
	44 g kg^{-1}	[150]
	280 g person^{-1} yr$^{-1\,*}$	[155]
	280–540 g person^{-1} yr^{-1}	[142]
	28.0 ± 1.7 g–K_2O kg^{-1}	[154]
	0.75–0.88 g person^{-1} d^{-1}	[146]
***Tot*–P**	4.8–9.8 g kg^{-1}	[156]
	1.83 g kg^{-1}	[157]
	0.5 g person^{-1} d$^{-1\,*}$	[141]
	0.3–1.7 g person^{-1} d^{-1}	[140]
	3 g kg^{-1}	[150]
	250 g person^{-1} yr$^{-1\,*}$	[155]
	126–250 g person^{-1} yr^{-1}	[142]
	3.59 g kg^{-1}	[20]
	0.9–2.7 g person^{-1} d^{-1}	[146]
	11.0 ± 2.0 g–P_2O_5 kg^{-1}	[154]
***Tot*–N**	0.96 g person^{-1} d^{-1}	[158]
	0.25–4.2 g person^{-1} d^{-1}	[140]
	18 g kg^{-1}	[150]
	710 g person^{-1} yr$^{-1\,*}$	[155]
	0.9–4.9 g person^{-1} d^{-1}	[17]
	1.5 g person^{-1} d^{-1}	[50]
	630–710 g person^{-1} yr^{-1}	[142]
	41.0 ± 4.0 g kg^{-1}	[154]
NH_4^+–N	0.1–0.2 g person^{-1} d^{-1}	[141]
	214 ± 4 mM	[137]
	1.4–2.9 mmol d^{-1}	[153]
NO_3–N	829–1678 μg kg^{-1}	[153]

* includes toilet paper use

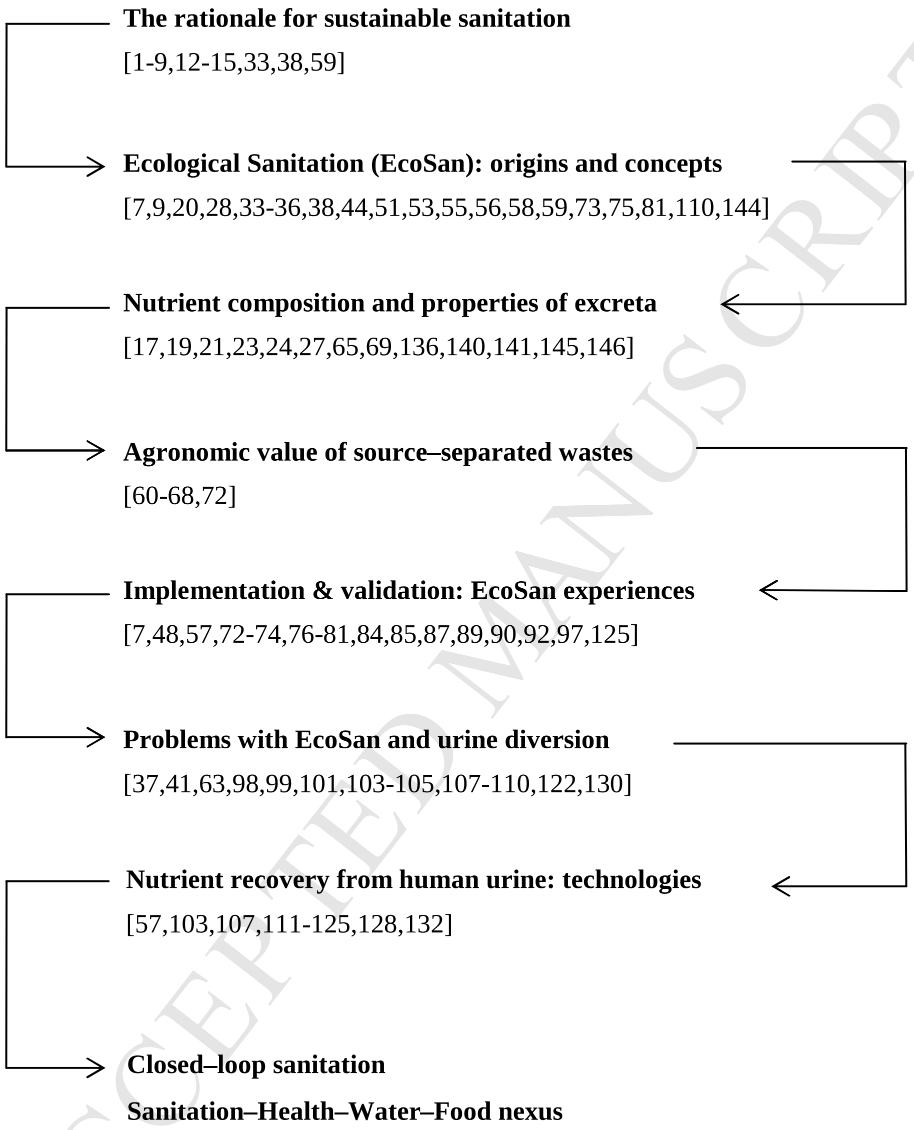

Fig. 1. Schematic representation of the literature analysis (select articles) for EcoSan and nutrient recovery from human urine.