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# Nutrient recovery technologies for management of blackwater: A review

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Nutrient recovery and recycling are of great importance in sustainable development. Blackwater (BW) refers to wastewater from toilets, which contains feces, urine, water, and toilet paper from flush toilets. The highly concentrated nutrients of blackwater could be collected through source separation and treated adequately to recover nutrients efficiently and economically. The review intends to give an overview of the characteristics of BW and different techniques to recover nutrients and other valuable products. A number of these technologies are currently under development or being tested at laboratory or pilot scale. The perspective for blackwater nutrient recovery technologies is very positive due to their great potential. For application of source-oriented sanitation infrastructure and systems, there is still a long way to go for development of commercial technologies and valuable products.

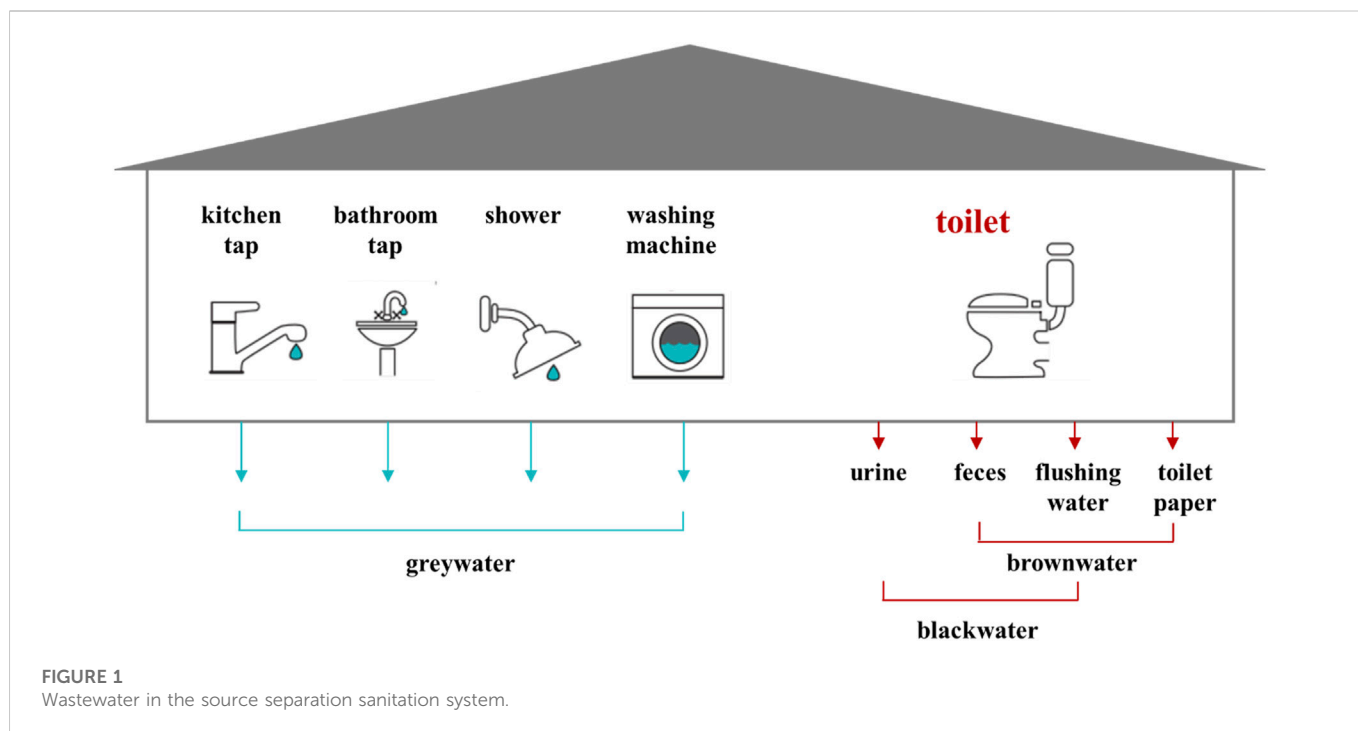
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blackwater, toilet, feces, urine, source separation, nutrient recovery

## 1 Introduction

Issues related to the decreasing quality and quantity of freshwater resources, which may be partly due to the currently applied sanitation systems, are becoming increasingly serious. In response to the limits of these sanitation systems, alternative solutions focusing on source separation and resource recovery, besides hygiene and environmental protection, are gradually emerging. Such solutions show great potential for promoting environmental and ecological sustainable development. Generally, wastewater streams (as shown in [Figure 1](#)) can be separated into greywater and blackwater (BW). Compared with mixed wastewater treatment, greywater recovery involves smaller hygienic concerns, has a reduced “yuck” factor, and demands less treatment effort. Furthermore, energy and nutrients are more easily recovered from BW ([Larsen et al., 2016](#)). [Thibodeau et al. \(2014\)](#) compared a BW source-separation sanitation system and a conventional system using life cycle assessment and environmental life cycle costing to show that the former is significantly superior to the latter in terms of climate change, resources, and human health, although their cost remains comparable.

BW refers to wastewater sourced exclusively from toilets; thus, it consists of urine, feces, toilet paper, and flushing water. It also contains large amounts of nutrients, around half of the domestic COD load, and the major proportion of pathogens excreted from the human body ([Otterpohl, 2002](#); [Vinnerås, 2007](#); [Fidjeland et al., 2015](#)). According to the calculated estimation



**TABLE 1** Calculated estimation of the yearly nutrients in urine and feces (source: Larsen et al., 2016; Malila et al., 2019; Otterpohl, 2002; Stintzing and Salomon, 2004).

Fraction	COD (kg/a/person)	N (kg/a/person)	P (kg/a/person)	K (kg/a/person)
Urine	3.6–4.4	1.9–4.1	0.2–0.4	0.9–1.3
Feces	14.0–15.0	0.2–0.5	0.1–0.2	0.3–0.5
Total	17.6–19.4	2.1–4.6	0.3–0.6	1.2–1.8

in Table 1, the amounts of nutrients (N, P, and K) are considerable for resource recovery. Besides, according to the analysis of Mihelcic et al. (2011), the K available from urine was approximately 1.68 million metric tons (with a similar mass available in feces). If collected appropriately, the K available from urine and feces could account for 22% of the total global K demand. Researchers estimate that, in 2050, the available K from urine associated with the population increase only will increase to 2.16 million metric tons (with a similar mass available in feces). Because of its specific composition, BW requires separate collection, less dilution, adequate treatment and final recycling of the nutrients.

Applying source-separation systems in rural areas may enable the recovery of four times more K and over thirty times more N compared with those obtained in current wastewater treatment systems (Malila et al., 2019). Kjerstadius et al. (2017) used an attributional life cycle assessment to investigate the carbon footprint and potential for nutrient recovery of two sanitation systems for a hypothetical urban area in Southern Sweden. The carbon footprint and nutrient recovery (P and N) results obtained revealed that the source separation system could increase nutrient recovery while decreasing the carbon footprint to a greater extent compared with the conventional system. Therefore, if properly managed, BW may provide not only a source of different valuable resources, such as nutrients, energy, and reclaimed water, but also multiple benefits to society. Nutrient recovery

**TABLE 2** Characteristics of feces found in the literature (source: Levitt and Duane, 1972; Otterpohl, 2002; Penn et al., 2018; Rose et al., 2015).

Parameter	Urine	Feces
Water content	>99 wt%	63–86 wt%
TS	<1 wt%	14–37 wt%
VS	—	92 wt% of TS
Carbohydrates	—	25 wt% of TS
Protein	—	2–25 wt% of TS
Fats	—	8.7–16 wt% of TS
COD	6,000–10,000 mg/L	—
TN	5,000–9,200 mg/L	5–7 wt% of TS
TP	300–2000 mg/L	—
pH	6.2–9.1	5.3–7.5

technologies for BW have drawn great concerns but are far from well development.

In this article, a overview of the characteristics of BW and different techniques to recover nutrients and other valuable products are given.

TABLE 3 Blackwater characteristics from different sewerage system.

Toilet flushing system	Parameter								Country/References
	pH	COD <sub>tot</sub> (g/L)	COD <sub>sol</sub> (g/L)	TN (mg/L)	TAN (mg/L)	TP (mg/L)	TK (mg/L)	TS (%)	
No water mixture	—	—	32.333	7,067–8,867	—	1,266	2,200	—	Germany/(Otterpohl (2002))
Conventional/dual flush toilet (5–9 L water per flush)	8.9–9.1	—	0.8–3.1	130–180	19	21–58	—	—	Sweden/(Palmquist and Hanæus (2005))
		1.290	—	162	121	21	—	—	China/(Ren et al. (2018))
	8.5	4.6	1.7	—	120.9	—	—	—	Canada/(Florentino et al. (2019))
	8.4	2.6	0.9	—	68.6	—	—	—	Canada/(Florentino et al. (2019))
	8.5	4.7	3.1	410	182	70.5	—	3.6	Canada/(Gao et al. (2019b))
	8.4	2.6	1.6	190	96.4	38	—	2.4	Canada/(Gao et al. (2019b))
Vacuum toilet (~1 L water per flush)	8.8	9.8	3.4	1900	1,400	220	—	—	Netherlands/(de Graaff et al. (2010))
	8.6	29.5	19.3	1700	1,040	330	—	17.1	Canada/(Gao et al. (2019b))
	8.2	18.5	4.8	—	1,595	—	—	—	Canada/(Florentino et al. (2019))

This work can also help researchers develop ideas concerning future research areas and make more informed decisions.

## 2 Characteristics of source-separated blackwater

BW includes urine, feces, and flushing water. Faecal sludge is raw or partially digested, a slurry or semisolid, and results from the collection, storage or treatment of combinations of excreta and blackwater, with or without greywater. In specific cases, the characteristics of faecal sludge are similar to BW. The characteristics of urine and feces vary widely depending on person's health and diet, as presented in Table 2. Flushing water is also an important factor which determines the concentrations of nutrients in BW. Generally, three toilet flushing system were commonly mentioned in literatures, i.e., conventional toilet (using 9 L water per flush), dual-flush toilet (using 3/6 L water per flush), and vacuum toilet (using .5/1.2 L water per flush) (de Graaff et al., 2010; Gao et al., 2019b). As shown in Table 3, the characteristics of BW varied widely in different source-separated systems. Compared with conventional toilet and dual-flush toilet, the sewage system employed vacuum toilet obtains more concentrated BW, which generally is beneficial for nutrient recovery, however, Gao et al. (2019a) figured out that BW from vacuum toilet exhibited lower bio-methane potential than that from conventional/dual-flush toilet because of ammonia inhibition. In domestic sewage, BW includes about 97% N, while greywater only includes about 3% N (Otterpohl, 2002). Considering the high concentration of N in BW, ammonia inhibition is one of the main challenges when employing biotechnology for nutrient recovery. However, as real BW has

highly variable characteristics and involves pathogenic and individual feces, it is difficult to execute repeatable experiments. In literatures, synthetic feces were commonly used for providing consistently reproducible substrate and alleviating these challenges. Penn et al. (2018) provide a critical literature review of synthetic feces and faecal sludge used for human waste related research.

## 3 Nutrient recovery technologies for blackwater treatment

For safe and clean nutrient recovery from BW, multiple-step treatment processes are required. In this part, the individual core processes employed in research or practical applications are presented firstly. As urine and feces are collected separately in some specific systems, the raw materials for nutrient recovery technologies include urine, feces, and BW.

### 3.1 Physicochemical processes

Processes for nutrient recovery by physicochemical means reported in the literature are summarized in Table 4, including evaporation, precipitation, pyrolysis, drying, and adsorption.

#### 3.1.1 Evaporation

Evaporation is a simple technology for removing water from urine to recover water and concentrated hygienized liquid fertilizer or even solid fertilizer. It is often used to recycle water of the best possible quality from urine in space applications. Some pilot projects for nutrient recovery have been tested in Germany,

TABLE 4 Physicochemical processes for blackwater treatment.

Process	Raw waste flow	Main effect	Target product	Remarks	References
Evaporation	urine	Volume reduction and hygienization	Water, concentrated fertilizer (N,P,K recovery)	High temperature has hygienization effect	(Antonini et al. (2012); Pahore et al. (2012); Zhang L et al. (2023))
Freeze-thaw	urine	Volume reduction	concentrated fertilizer (N,P,K recovery)	—	(Maurer et al. (2006); Ganrot et al. (2007); Moharramzadeh et al. (2022))
Reverse osmosis	urine	Volume reduction	concentrated liquid fertilizer (N,P,K recovery)	Hygienization measures should be added	(Pathy et al. (2021); Courtney and Randall (2022a); Courtney and Randall (2022b))
Acidification	urine	preventing urea hydrolysis with pH lower than 4	Liquid fertilizer (N,P,K recovery), urea is main N- chemical	Neutralization is necessary before it can be used as fertilizer	(Hellström et al. (1999); Maurer et al. (2006); Saetta et al. (2020))
Ion exchange	urine	Ion exchange by zeolite or polymeric macro net exchanger	N recovery	—	(Maurer et al. (2006); Landry et al. (2015))
Electro-dialysis	Urine	salts to be extracted and concentrated	N recovery	—	(Pronk et al. (2006); Chen et al. (2020); Rodrigues et al. (2020))
Isobutylaldehyde-diurea (IBDU) precipitation	Urine	Chemical precipitate	N recovery	non-hydrolyzed urine should be used	Maurer et al. (2006)
Struvite precipitation	urine or liquid digestate of blackwater	To form the chemical precipitate of MAP	N and P recovery	Addition of magnesium is required	(Ronteltap et al. (2010); Hug and Udert (2013); Ishii and Boyer (2015); Tansel et al. (2018); Aguado et al. (2019); Wu et al. (2022))
Ammonia stripping	Urine or liquid digestate of blackwater	stripped under vacuum or atmospheric pressure	N recovery	pH should be adjusted to more than 12	(Liu et al. (2015); Xu et al. (2017); Wu et al. (2022))
Pyrolysis	Brown water or blackwater	Chemical conversion	Biochar	—	(Liu et al. (2014); Krueger et al. (2021))
Hydro-thermal carbonization	Brown water or blackwater	Chemical conversion	Biochar or hydrochar	—	(Danso-Boateng et al. (2013); Danso-Boateng et al. (2015); Fakkaew et al. (2015); Yahav Spitzer et al. (2018))
Hydro-thermal liquefaction	Brown water or blackwater	Chemical conversion	Biocrude oil	Co-HTL could improves the yield and fuel composition that exhibits a higher energy value of biocrude. Co-liquefaction	(Watson et al. (2017); Hossain et al. (2022); Kabir and Khalekuzzaman (2022))
Convective drying	Brown water or blackwater	Moisture removal	Fertilizer or fuel	Solar and wind energy could assist to improve the economical efficiency for application	(Pocock et al. (2022); Seodigeng et al. (2022); Venkata Sai and Reddy (2022))
Biochar adsorption	Urine or blackwater	adsorption	Fertilizer (N,P,K recovery)	The properties of biochar, such as surface area, surface functional groups, and metal oxides modification, are important for nutrient recovery	(Liu et al. (2021); Pathy et al. (2021); Mamera et al. (2022))

Vietnam, and Canada (Antonini et al., 2012; Pahore et al., 2012; Bethune et al., 2015). The boiling point of the urine is 130°C, which is very high compared to the boiling point of water. This suggests that almost all water can be removed with minimal loss of the nutrient from urine with the loss of ammonia nitrogen (Patel et al., 2020). Urine evaporation is challenged by two major issues: ammonia loss and high energy consumption. Unless conducted in a sealed environment or reclaimed by ammonia stripping, up to 93% of the nitrogen bound in ammonia can be lost due to volatilization during urine evaporation (Chipako and Randall, 2020). Inhibition of urea hydrolysis, acidification, energy recovery, and solar energy utilization have been investigated and

tested at the pilot scale to address these problems. Hydrochloric acid, acetic acid, sulfuric acid, and phosphoric acid have been reported succeeded in inhibiting urea hydrolysis by maintaining acidic conditions (Saetta et al., 2020; Moharramzadeh et al., 2022; Zuo et al., 2022). Ren et al. (2021) improved urea stabilization by nitrification at a 100 L pilot-scale aerobic MBR reactor, successfully converted 50% of the ammonia into nitrate and obtained vapour flux at 1.3 kg m<sup>-2</sup> h<sup>-1</sup> as well as high solar to vapour conversion efficiency of 87% by heat localized solar evaporation. The solar evaporation efficiency could be improved by developing photothermal conversion materials. Zhang L et al. (2023) recover 1.1 kg·m<sup>-2</sup> of condensed freshwater (meeting WHO

TABLE 5 Biological processes for blackwater treatment.

Process	Raw waste flow	Main effect	Target product	Remarks	References
Anaerobic digestion	blackwater or brown water	Organic matter degradation and hygienization	Biogas, organic matter, N, P, K recovery	Post-treatment is necessary	(Mang and Li (2010); Florentino et al. (2019); Xu et al. (2019))
Composting	blackwater or brown water	Organic matter degradation and hygienization	Compost fertilizer	Dewatering before composting may be necessary	(Vinnerås (2007); Mahmood et al. (2015); Oarga Mulec et al. (2016); Zhu et al. (2022))
Partial nitrification	urine	Partial nitrification to form Nitrate	Ammonium recovery	—	(Hellström et al. (1999); Udert et al. (2003); Fumasoli et al. (2016); Zhang et al. (2019))
Storage	urine	Ammonification and pH increase could inactivate the pathogens	Liquid fertilizer (N,P,K recovery)	Temperature and storage time are also key factors	(Hellström et al. (1999); Maurer et al. (2006); Pahore et al. (2012); Saetta et al. (2020))
Microalgae-based method	Urine or blackwater	Organic matter degradation and inactivate the pathogens	Microalgae	Algal-bacterial aerobic granular sludge could be used for blackwater treatment	(Li et al. (2018); Žitnik et al. (2019))

standards for drinkable water) from urine at 7.5 h under a low light intensity using cotton cloth photothermal conversion film-monolithic hydrophobic.

### 3.1.2 Precipitation

Struvite precipitation is a chemical reaction in which ammonia and phosphate are reacted with magnesium salt under alkaline conditions to form struvite  $[\text{Mg}(\text{NH}_4)(\text{PO}_4)\cdot 6\text{H}_2\text{O}]$ , MAP], which is an easily separable solid substance known to be a slow-release fertilizer. The pH of hydrolyzed urine (approximately 9) is suitable for struvite precipitation. Struvite precipitation generally has high removal efficiency and low initial operation cost (Pathy et al., 2021). Wei et al. (2018) recovered struvite and ammonium sulfate from urine at a pilot scale precipitation facility and achieved 94% struvite precipitation efficiency and 93% removal efficiencies for nitrogen. For forming struvite, human urine contains an excess of ammonium relative to phosphate but is deficient in Mg. Precipitation is triggered by addition of Mg, usually in the form of  $\text{MgO}$ ,  $\text{Mg}(\text{OH})_2$ ,  $\text{MgCl}_2$ , or bittern (Maurer et al., 2006). Struvite precipitation has been extensively investigated to remove N and P from different water flows, such as digester supernatants, animal waste slurries, and landfill leachate, among others. Many laboratory studies and pilot scale experiments have also been conducted for N and P recovery from urine and BW (Ishii and Boyer, 2015; Tansel et al., 2018; Wang J et al., 2018; Wei et al., 2018; Aguado et al., 2019; Huang et al., 2019b). Li X et al. (2022) recovered phosphate as struvite from BW and obtained a high recovery rate of phosphorus (>98%) by recovering product struvite with a median particle size of 32.96  $\mu\text{m}$ , then conducting a pilot-scale test with a rural public toilet in Xiong'an New District, Hebei Province. Struvite precipitation has been used for N and P recovery from hydrolyzed urine in the Netherlands, Sweden, Germany, and Vietnam at the pilot scale (Winker et al., 2009; Wei et al., 2018).

However, the purity of the actual struvite production is generally only 30%–50% due to the simultaneous crystallization of Ca-P and  $\text{CaCO}_3$  during the recovery process (Zhang et al., 2022). Ongoing efforts are made to create new struvite productions. Recovery of calcium phosphate is attractive as calcium phosphate products (such as  $\text{Ca}(\text{H}_2\text{PO}_4)_2\cdot 2\text{H}_2\text{O}$  and  $\text{CaHPO}_4\cdot 2\text{H}_2\text{O}$ ) have comparable

fertilization efficiency with struvite, and it has diverse applications in manufacturing (Tervahauta et al., 2014). Zhang B et al. (2023) harvest nutrients from hydrolyzed human urine *via* precisely regulating Ca/P dosing ratio, resulting in a P recovery efficiency of 100% and a purity for calcium phosphate of above 90%. K-struvite (i.e., magnesium potassium phosphate) can be harvested by potassium struvite precipitation (Wilsenach et al., 2007; Xu et al., 2015). In this case, the maximum P recovery efficiency could reach 100%, while the K recovery efficiency was relatively low. Tervahauta et al. (2014) harvested calcium phosphate granulation without any addition of chemicals, proving that only 2% of the incoming K in the upflow anaerobic sludge blanket (UASB) reactor can be recovered with the calcium phosphate granules. Huang et al. (2019a) improved the K-struvite crystallization by using different additions, obtaining a K recovery efficiency of 25%–70%. Huang et al. (2019b) further observed the Na-struvite formation in the case that the P recovery efficiency was 96% and the Na content in the precipitates was 67 mg/g.

### 3.1.3 Pyrolysis

Pyrolysis (Liu et al., 2014; Yacob et al., 2018; Krueger et al., 2021), hydrothermal carbonization (Danso-Boateng et al., 2013; Danso-Boateng et al., 2015; Fakkaew et al., 2015; Fakkaew et al., 2018), and hydrothermal liquefaction (HTL) (Lu et al., 2017; Watson et al., 2017; Wang W et al., 2018; Hossain et al., 2022) are three thermochemical conversion processes conducted under different temperatures and pressures to hygienize and mineralize human feces from BW or brown water and produce valuable byproducts, such as biochar, hydro-char, and bio-crude oil. Given the high water content in BW, HTL is the most frequently used technology where water is directly used as a liquefacient (Xi et al., 2022). The HTL continuous reactor has been developed to provide efficient energy balance (Elliott et al., 2015). Some assistant methods have been conducted to improve the heating efficiency, such as microwave technology, electricity-driven method (Xi et al., 2022) and catalyst (Wang W et al., 2018). Afolabi and Sohail (2017) give an overview of treat and recover value from BW by microwave heating technology. Although such processes have only been tested at the laboratory scale, they also show great potential for practical applications in the near future.

### 3.1.4 Drying

Drying provokes the removal of moisture through natural drying, mechanical drying, or convective drying with hot air (Ling et al., 2022). It reduces the mass and volume, further destroys the pathogenic organisms due to the combined effect of heat and moisture removal during drying. The convective drying method is already widely studied in the wastewater sludge treatment, focusing on the direction of thin-layer drying, fluidized bed drying, spray drying and pneumatic drying. Solar energy can be used to reduce the cost of drying (Bennamoun, 2012). The thin-layer drying method could be improved by assisting with ultrasonic, microwave, and desiccant. Ling et al. (2022) systematically reviews the convective drying technology of sludge. However, the studies on convective drying of BW are still far from well developed. Feces and faecal sludge originates from onsite sanitation without greywater are suitable for drying. The dried product could be used as an organic fertilizer with a particularly high phosphorous content and a slow release of nitrogen and phosphorous (Septien et al., 2020). Besides, with high heating value, it could also be used as fuel.

Faecal sludge from ventilated improved pit latrines was dried in a convective drying thermobalance by varying the temperature from 40°C to 80°C, resulting in a drying rate ranging between 1 and 40 g/min/m<sup>2</sup> and a moisture content of dried products ranging between 2.4 and 3.2 g/g db (Pocock et al., 2022). Seodigeng et al. (2022) dried human faeces using solar and wind energy under ambient conditions and further developed thin-layer drying semiempirical models. Venkata Sai and Reddy (2022) proposed a solar energy drying system of BW treatment with a BW capacity of 2.4 kg/day in which the moisture content of BW was reduced from 70% (w.b.) to 6.82% (w.b.). The drying technology could be combined with non-sewered sanitation system to provide safe local discharge and efficient nutrient/energy recovery.

### 3.1.5 Adsorption

Adsorbents such as biochar, zeolite, resins, activated carbon, alumina, and silica gel have been extensively studied for the nutrients recovery from urine (Patel et al., 2020). The adsorption efficiency of ammonium and potassium are not concerned with urine dilution, while the adsorption efficiency of orthophosphate is different for different diluted urine solutions. Adsorption of ammonium from urine on to the zeolites can be achieved up to 100% under appropriate conditions. In terms of the adsorption of ammonium, resins gave the highest efficiency for the ammonium compared to the zeolite and biochar (Tarpeh et al., 2017).

Biochar, produced from the wastes through a process in which biomass wastes such as agricultural forest residue, food waste, solid waste, animal waste, and municipal sludge thermally decomposed in oxygen-less environmental conditions, is gaining the researcher's attention in recent years (Li J et al., 2022). It is comparatively more economical compared with other conventional adsorbents due to adding value to the management of waste products at the same time (Pathy et al., 2021). The nutrient-loaded biochar can be directly applied in the agricultural field to act as slow realizing fertilizer and soil conditioner with no need for any other special treatment. The mechanisms of biochar adsorption include ion exchange; electrostatic interaction; formation of hydrogen bond; exchange of ligand; precipitation on the surface; complex formation between the target molecule and functional group present on the biochar surface and/or either through physical adsorption (Huang et al., 2020). Thus,

researchers tried to increase the efficiency of nutrients recovery by improving the adsorbate properties of biochar, including increasing surface area, loading surface functional groups, modification with various metal oxides, adjusting environmental parameters (Pathy et al., 2021). Liu et al. (2021) recovered more than 70% of phosphate in the simulated urine using waste straw biochar modified with the Mg/Fe bimetallic oxide with a maximum adsorption capacity of 206.2 mg/g. Pathy et al. (2021) deliberated possible strategies of preparing engineered biochar aimed for recovering nutrients from urine with the potential challenges and opportunities in a review.

Biochar can also recovery nutrients and remove *E. coli* and faecal coliform bacteria from BW. Mamera et al. (2022) removed 89%–98% bacteria and recovered 68% N and 98% P from faecal sludge using pinewood biochar through different soil-bed biochar column. Besides the adsorbate properties of biochar, the solid content significantly impacts the efficiency of recovering nutrients from BW by biochar. However, the studies on recovering nutrients from BW by biochar are still insufficient. It generally act as additive for improving anaerobic digestion in terms of applying biochar in BW treatment.

## 3.2 Biological processes

Because of their low cost and easy operation and maintenance, biological treatment processes have been widely applied for BW, faecal sludge, or brown water treatment. Anaerobic digestion, composting, and partial nitrification processes are mainly used for nutrient recovery. Table 5 summarizes biological treatment processes.

### 3.2.1 Anaerobic digestion

Anaerobic digestion plays a key role as a well-known treatment technology for hygienizing concentrated wastewater, such as BW. Low water consumption helps achieve a low dilution of BW, which provides a good basis for efficient nutrient recovery. Thus, low-flush or vacuum toilets are preferred when collecting BW for anaerobic digestion (Mang and Li, 2010). Different types of digesters, such as anaerobic baffled reactors (ABRs), UASBs, continuous stirred tank reactors at the industrial level, as well as fixed domes, water jacked floating drums, and prefabricated plastic and glass fiber digesters at the household level (Luostarinen et al., 2007; Wendland et al., 2007; de Graaff et al., 2010), have been used for anaerobic digestion according to the characteristics of BW and hygienization demands.

Anaerobic digestion does not remove nutrients valuable as fertilizer and, therefore, presents an appropriate BW treatment for the agricultural cycle when combined with safe pasteurization. In practice, several factors drive the anaerobic digestion of BW within the scope of resource management sanitation:

- Safe sanitation: The hazardous compounds in excreta, pathogens, and medical residues, which present serious dangers to public health, are not spread in the water cycle.
- Production of biogas for cooking, lighting and electricity: The produced biogas is a reliable renewable energy source.
- Nutrients recovery for agriculture: The residues of anaerobic digestion are valuable fertilizers.
- Water saving: The application of pour or low-flush technology reduces the consumption of high-quality drinking water.

The efficiency of anaerobic processes depends on many influencing factors, such as temperature, the characteristics and concentration of organic matter, mass transfer, and fluctuations in composition and load, among others. Because of high N in BW, ammonia inhibition is a matter of concern which might inhibit microbial activities and reduce COD removal and methane production efficiencies. Fuchs et al. (2018) reviewed the state of technology as well as recent achievements and perspectives on tackling ammonia inhibition in anaerobic digestion.

BW can also be anaerobically co-digested with kitchen waste or other organic matter to improve the efficiency of biogas production (Gunnarsdóttir et al., 2014; Rajagopal et al., 2014; Hertel et al., 2015; Wang et al., 2020). The microbial community dynamics and inhibition effects of anaerobic digesters on BW have also been investigated (Gao et al., 2019a; Gao et al., 2019b).

Measures to enhance anaerobic digestion, such as granular activated carbon-assisted digestion, biochar addition, and zero-valent Fe addition, have been investigated (Florentino et al., 2019; Pan et al., 2019; Xu et al., 2019). Mamera et al. (2022) figured out that biochar contributed to remove N, P, *E. coli* and faecal coliform bacteria in BW.

Anaerobic digestion of BW or faecal sludge has been widely used at the household and residential levels and even in large-scale plants (Mang and Li, 2010). Post-treatment processes, such as solid/liquid separation, composting, and disinfection, should be integrated to achieve complete nutrient recycling (Mahmood et al., 2015; Thostenson et al., 2018). One large-scale co-digestion project can treat up to 400 tons of faecal sludge per day from septic tanks in Ouagadougou, Burkina Faso. This biogas system has a production capacity of approximately 5,000 m<sup>3</sup> biogas daily. Aerobic methods were also tried in some cases. Barrios-Hernández et al. (2020) co-treated synthetic faecal sludge with municipal synthetic wastewater in an aerobic granular sludge reactor, however, the addition of faecal sludge decreased the sludge settle-ability and reduced the average granular size. More efforts are necessary to improve the efficiency and consistency for full-scale application.

### 3.2.2 Composting

Composting is an aerobic biological process that converts solid organic matter into stabilized organic compost, CO<sub>2</sub>, water, and other gases. Excessive heat energy generated in on-site composting due to microbes activity, peak temperatures during the thermophilic phase can reach up to 70°C (Zhou et al., 2022), thus the pathogens in BW could be killed by the high temperature. Proper composting of organic matter yields a nuisance-free, humus-like material that can be used as a soil conditioner in agriculture. Spreading BW compost on fields can improve the soil structure and raise the tolerance of plants to salts (Oarga Mulec et al., 2016).

A bulking agent, such as saw dust or wood chips, is usually added to reduce the moisture content of the raw material and improve its C:N ratio. Several studies on the composting of fecal matter and solid fraction of BW have been carried out (Vinnerås, 2007; Oarga Mulec et al., 2016). The effect of different bulking materials as a supporting matrix on the solid fraction of BW composting in terms of pathogen inactivation, nutrient loss, and CH<sub>4</sub> emission have been studied (Oarga-Mulec et al., 2019). Zhu et al. (2022) composted faecal sludge with sawdust and rice straw in earthworm-based system and obtained significant promote in composting efficiency and global warming potential reduction.

Composting of human excreta from waterless toilets and the solid fraction or digestate of BW has been applied in practice. In cold regions, greenhouses could be used to keep a relatively constant ambient temperature for composting processes (Mahmood et al., 2015).

### 3.2.3 Partial nitrification

Nitrification refers to the biological oxidation of ammonia or ammonium to nitrite, followed by oxidation of nitrite to nitrate. Nitrification of urine can only oxidize half of the available ammonium until nitrification ceases due to low pH conditions and the absence of other relevant buffers at significant concentrations in urine (Maurer et al., 2006; Feng et al., 2008).

Experiments conducted by Udert and Wachter (2012), Udert et al. (2003) and other researchers reveal that the product of urine nitrification is either an ammonium-nitrate or ammonium-nitrite solution with an approximate composition of 1:1; urine nitrification could stabilize the free ammonia in the solution to prevent the nitrogen release loss from the urine. Fumasoli et al. (2016) employed a combined nitrification/distillation process to stabilize urine and concentrate the nutrient solution at the pilot scale to produce liquid fertilizer.

### 3.2.4 Urine storage

Urine storage seems to be a physical process, but, during storage, urea can be hydrolyzed by enzyme urease, which is a biological process. Urea is transformed into ammonia and ammonium, leading to a pH increase. Experimental results have revealed that temperature and elevated pH (to 9), in combination with ammonia, can affect the inactivation of microorganisms. The storage time also plays an important role in urine hygienization (Maurer et al., 2006). Inactivation of typical enteric pathogens and model organisms has been studied for hygienization by urine storage under different conditions of urine dilution and temperatures (Vinnerås et al., 2008). The results of this research showed that the recommended storage time for urine (i.e., 6 months at 20°C or higher) is safe for unrestricted use and could probably be shortened, especially for undiluted urine (Vinnerås et al., 2008).

Urine storage has been widely applied to hygienization and urine utilization as fertilizer at the household and residential levels in many countries, such as Sweden, Germany, Switzerland, China, and some African countries (Hanæus et al., 1997; Alemayehu et al., 2020).

### 3.2.5 Microalgae-based nutrient recovery

Microalgae contains high oil content of 20%–50% on a dry weight basis and are efficient in removing nitrogen, phosphorus from BW and urine (Zubair et al., 2020; Nguyen et al., 2021). Different microalgae species have various efficiency on nutrients recovery. *Chlorella sp.* shows great tolerance to ammonia and can recovery 23%–100% N and 20%–100% P, respectively (Khan and Yoshida, 2008). Pathogens could be inhibited during the microalgae-based nutrient recovery process. Žitnik et al. (2019) removed 12%–51% *E. coli* from BW treated with microalgae *Chlorella vulgaris*.

As heterotrophic bacteria could decompose organic matter and promote plant growth by complex communication mechanisms and nutrient exchange, algal-bacterial systems were conducted to treat wastewater (Ramanan et al., 2016). In algal-bacterial systems, oxygen and organic carbon produced by microalgal photosynthesis could be used by heterotrophic bacteria while CO<sub>2</sub> released by

chemoorganotrophic bacterial respiration could be in turn fixed by algae (Li et al., 2018). Li et al. (2018) studied bacterium *Vibrio. sp* Y1-5 and microalgae *S. platensis* in their mutualistic system, obtaining a biomass yield of 4.28 g/L and recovering 86% of nitrogen and 91% of phosphorus. Algal-bacterial aerobic granular sludge is an emerging new method for wastewater treatment with more potentials for meeting the demands of sustainable bioeconomy due to its lower energy demand, higher nutrients removal, better biomass settleability, and CO<sub>2</sub> capture capacity (Lee and Lei, 2019; Chen et al., 2022; Lee and Lei, 2022). However, further researches on recovering nutrients from BW by algal-bacterial aerobic granular sludge are required and meaningful.

## 4 Conclusions and perspectives

This paper summarizes and reviews currently available processes for nutrient recovery of BW, urine, and feces. In most cases, nutrient recovery requires a treatment system consisting of multiple steps not only for nutrient recovery but also for discharge control and removal of harmful substances (Kakimoto et al., 2007).

A wide range of technological options are available for nutrient recovery from BW. Depending on the overall goal of the resource-oriented treatment process, a specific technical solution or combination of technologies may be determined to meet requirements. However, most of the techniques developed thus far present different weaknesses that limit their practical applications. Future BW treatment solutions will likely consist of a combination of treatment processes, for example, recovery of biogas energy by anaerobic digestion, followed by recovery of N and P by struvite precipitation, solid/liquid digestate separation, and then composting for solid digestates.

Source separation has shown to be advantageous for improving treatment capacity, food security, and efficiency; however, these systems are still immature and considered risky by professionals and, thus, scarcely implemented (McConville et al., 2017; Trimmer et al., 2019). Possible barriers to the practical application of these systems may include:

- Unproven technologies in practices
- Unproven cost benefit in comparison with conventional wastewater systems
- Complex operations and maintenance
- Lack of a source control collection system,
- Fluctuation of the target product value.

Therefore, additional research is needed to improve or enhance existing processes and find promising process combinations with great effectiveness.

However, non-sewered sanitation system, that is not connected to a networked sewer, and collects, conveys, and fully treats BW to allow for safe reuse or disposal, is a practical option for BW treatment and

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resource recovery. Non-sewered sanitation system was awarded as one of the top 10 breakthrough technologies in 2019 by MIT Technology Review (Winick, 2019), seems a feasible solution for decentralized BW management (Cheng et al., 2022). The developed technologies are useful for such systems.

Overall, the perspective for resource-oriented BW management technologies is very positive due to their great potential. More attention should be paid and more efforts should be spent to develop efficient technologies and improve the feasibility, reliability, economy, environment friendliness, and agronomic value of recovered products. It provides clear evidence that resource-oriented technologies are very important tools for sustainable development.

## Author contributions

XW and ZL written the manuscript. JC, SC, H-PM, LZ, HH, and IJ discussed and edited the manuscript.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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