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Synergistic pathways to a circular bionutrient economy

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ABSTRACT

Bionutrient circularity can increase food system sustainability. Global food production currently depends substantially on synthetic fertilizers, while massive volumes of crop residues, food scraps, and excreta are undervalued and mismanaged, contributing to environmental degradation and climate change. Transforming these organic underutilized resources through combinations of physiochemical, biological, and thermochemical processes can improve public hygiene while keeping carbon and nutrients within the food system. By redirecting both organic matter and nutrients to soils, bionutrient circularity can offset fertilizer and energy costs. Meanwhile, circular feeds can enable livestock sectors to grow without increasing land demands for crop production, much of which is currently fed to livestock. Synergistic integration of transformation processes and resource recovery pathways will unlock substantial economic and environmental benefits. Realizing the potential of a circular bionutrient economy, however, will require robust management of contaminants, navigation of context-dependent tradeoffs, and integration of sociocultural, technical, operational and regulatory innovation processes.

1. Introduction

The circular bionutrient economy (CBE), defined as the circular economy of nutrients in managed organic residues (Lehmann et al., 2025), is a critical feature of a circular food system, which is in turn a key component of a broader circular economy. A circular economy aims to “design out waste, keep materials in circulation at their highest use, and regenerate nature” (Ellen MacArthur Foundation, 2013); here we explore several important pathways for applying these principles to the agrifood system through the concept of CBE, which reduces dependency on and conserves non-renewable resources by increasing the recycling of nutrients within the food system.

We consider physiochemical, biological, and thermochemical processes that can be used to transform three of the food system’s major organic by-products: crop residues, food scraps, and excreta. The pathways for circular utilization of the nutrients contained in these resources can form complex and synergistic webs of material flows that reduce polluting wastage, keep nutrients and carbon in the food system, and reduce pressure on natural systems through greater resource use efficiency in the food system. Significant efficiencies can be attained through synergies between carbon and nutrients in soils; between biological processes and biochar; among activities that produce and utilize organic materials; and among sectors.

The “modern” food system, often characterized as flowing from inputs to production to intermediation and finally to consumption, is both extraordinarily productive and extremely wasteful. This linear food system has been enabled, for the past century, by mined and manufactured nutrients that are applied to soils as fertilizer. This approach has led to enormous increases in cereal yields, but it has come with sustainability challenges (Tilman et al., 2002) in terms of both resource use and pollution. Synthetic nitrogen (N) supply chains (from production through use) account for an estimated 10.6 % of agricultural greenhouse gas (GHG) emissions, and 2.1 % of global GHG emissions (Menegat et al., 2022). Phosphorus (P) is a finite resource mined in only a few places in the world (Cordell et al., 2009), and concerns around diminishing P availability (and thus a rising cost of P fertilizer) have been widely noted (e.g., Nedelciu et al., 2020). While access to crop nutrients is a current challenge for many smallholder farmers in low-resource

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settings, the global levels of nutrient pollution produced by the prevailing food system (we include sanitation as part of a circular food system; Almaraz et al., 2022) exceed the safe planetary boundaries (Rosemarin et al., 2020).

We use the term “waste” to refer to materials that are un- or underutilized, and “resource” or “by-product” to refer to recyclable materials more neutrally, and “organic underutilized resources” (OURs) to refer to the specific resources of interest in this paper. Fig. 1 contrasts, in simplified fashion, aspects of linear and circular food systems. Fig. 1a identifies the selected wastes and harms of a linear food system that can be addressed through CBE. It would be desirable to reduce the use of synthetic fertilizer inputs where their use is adequate or excessive (replacing them with recycled nutrients to the extent possible), and to complement their use where nutrient inputs are currently inadequate. There is a need to reduce food wastage and to diminish the extent to which human-edible crops and fish are fed to livestock (van Zanten et al., 2019). Food scraps, food processing by-products, and the nutrients in excreta are deemed “waste” and treated as a disposal problem. The current nutrient paradigm is unsustainable for many reasons, including aquatic pollution, atmospheric GHG pollution, and other issues associated with synthetic fertilizers, the costs and embedded resources associated with food that is wasted (nutrients, labor, energy, land) and the problems in disposing of excreta and other wastes.

As illustrated in Fig. 1b, circular food systems reduce waste and keep nutrients and carbon in circulation through production of animal feeds, fertilizers, and soil amendments from food system byproducts. Additionally, CBE can contribute to regenerating nature in several ways. Averting methane production from landfilled organic materials and avoiding the GHG emissions associated with inorganic fertilizer production and use can reduce the food system’s contributions to climate change. Reducing water pollution from human and animal excreta and from fertilizer runoff can reduce the eutrophication of aquatic resources. The greatest benefit from CBE can be achieved in regions where soil organic matter and nutrient content critically limit food production, and where farmed area expansion occurs at the expense of natural areas to compensate for low land productivity, such as in much of Africa. As reflected in the adoption of container-based sanitation (World Bank Group, 2019), low-resource settings may also be the most readily able to achieve CBE because of the limited access to synthetic fertilizers and advanced sewage treatment, in addition to the lower costs of labor.

Here, we explore pathways through which three abundant OURs can be better exploited in circular food systems, focusing on selected processes that can lead to improved soil health and reduced dependency on synthetic fertilizers, and highlighting notable examples that could support increased food system circularity. We explore the concept of “highest use” for OURs, or how value can be maximally recovered as nutrients flow through the food system. We note potential hazards and synergies among the pathways and highlight the important role of thermochemical transformation in facilitating biological processes involved in various material transformations that yield food, feed, soil amendments and energy. We touch on some of the governance, policy and institutional factors that contribute to the ways in which CBE pathways are implemented or obstructed.

2. Transitions to bionutrient circularity in agrifood system

In conceptualizing pathways toward circular food systems, we consider major organic materials that are currently wasted or underutilized. Crop residues, food scraps, and excreta are of interest, firstly, because of their quantitative dominance as food system by-products, and secondly, because of their qualitative complementarity. Crop residues are produced on enormous scales and are not always put to their highest use. Nearly one third of the world’s food produced for human consumption is wasted, with a lost value of nearly a trillion USD each year (UN Environment Programme, 2021). Nearly all human excreta and a substantial proportion of animal excreta are wasted or underutilized (Devault et al., 2025). Crop residues are high in carbon while excreta and food scraps are high in nitrogen and other nutrients, such that these resources have synergistic potential for use in composting and other transformations (Tables 1 and 2). CBE pathways that recover and reuse the nutrients in these underutilized resources can benefit both the food system and the environment.

2.1. *Crop residues*

The residues (stalks, leaves, pods, etc.) that remain when crops are harvested may or may not be wasted, but they are not necessarily put to their highest (most beneficial, least harmful) use. Crop residues have many possible uses, serving as animal feed, fuel and energy production, ground cover, sources of soil organic matter, and other uses. While they can be contested resources, around 5–11 % of crop residues globally are burned (FAO, 2023; Smerald et al., 2023) when farmers prepare to plant the subsequent crop. This practice is particularly common in parts of Africa and South Asia, with negative impacts on air quality and public health, and substantial release of GHGs (Bhuvaneshwari et al., 2019). While crop residues contain significant amounts of nutrients, their principal elemental constituent is carbon in the forms of cellulose, hemicellulose and lignin. Crop residue management has important implications for soil health (Fu et al., 2021), and the quantity of crop residues available for novel circularity strategies is context specific. It may be possible to utilize crop residues for energy recovery and/or pyrolysis, followed by return of carbon and/or nutrients to soils, as discussed below.

Because much of human food and livestock feed comes from cereal crops, cereal residues are produced in vast quantities worldwide; 70 % of the world’s crop residues are from cereals, and an estimated 3.9 trillion metric tons of cereal residues were produced globally in 2020 (Smerald et al., 2023). Globally, 44 % of cereal residues are left on fields to contribute to the maintenance of soil organic matter, while 33 % of residues are used for animal feed and bedding. Table 1 shows the quantities of major cereal residues produced in selected countries and the carbon and nutrients they contain.

Prior analyses have explored the global potential for energy recovery from anaerobic digestion and thermochemical conversion of crop residues (Feng and Rosa, 2024; Paudel et al., 2024). The recycling of nutrients from anaerobic digestate following energy extraction from crop residues and animal manure offers significant potential for crop nutrition and GHG reduction (Marconi and Rosa, 2024). Some estimates suggest that 30 % of crop residues could be exported from a field without harm to soil health (e.g., Scarlat et al., 2010), while others point to more complex dynamics (e.g., Moebius-Clune et al., 2008; Mouratiadou et al., 2020). A general trend linking residue removal and decrease in soil organic carbon is both expected and often observed, with reductions of soil organic matter being more likely with higher rates of removal and longer periods of removal (Smith et al., 2012). However, as discussed below, returning the products of composting, pyrolysis or anaerobic digestion of cereal residues to fields would better support soil health goals than leaving unprocessed residues in place. For all of these, farmers and other stakeholders need support to understand their options for producing and using CBE products (compost, digestate, biochar), and to enable and incentivize their production and use (supportive regulations; carbon credits, subsidies for infrastructural investments). Certification infrastructure (including standards and testing capacity) may be as important as production infrastructure.

2.2. *Food scraps*

Over a third of food produced is lost or wasted globally (is not consumed by humans or animals), with nearly 20 % of food wasted at the retail, household, or food service levels (UNEP, 2024). Wastage amounted to around 2.5 billion tons in 2022, at an economic value of nearly a trillion USD. There are many ways that waste can be avoided

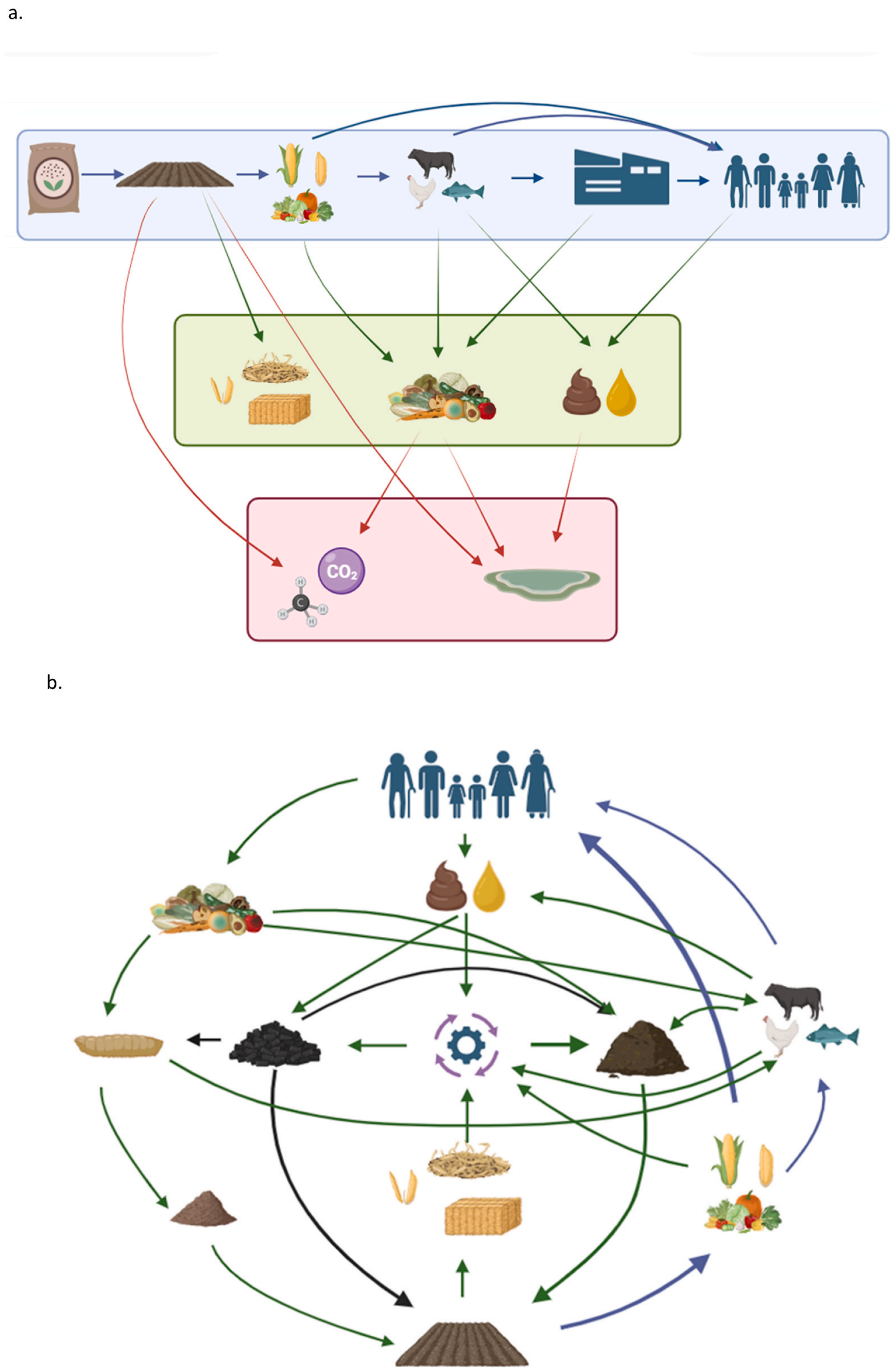

Fig. 1. Simplified schematic representations of carbon and nutrient flows in linear (1a) and circular (1b) food systems. 1a. The linear food system (in the blue box) produces three major by-products (in the green box) that, when wasted, contribute to greenhouse gas production, water pollution and other harms (in the red box). 1b. Selected carbon and nutrient flows in a circular bionutrient economy, highlighting the networked nature of the selected flows depicted. The focus here is on excreta, food scraps and crop residues, transformed through biological, physical and thermochemical processes in a circular food system. Processors, practicing at context-dependent scales and technical levels, process foodstuffs and transform by-products into fertilizers and other valuable products. Diets emphasize plant-based foods. Solid excreta are composted or thermochemically processed through pyrolysis to produce biochar; nutrients from urine and compost are captured on biochar. Food scraps are fed to animals (livestock or insects). Soils are enriched by return of excreta-derived nutrients and carbon from people, livestocks and insects, compost, and biochar in varying combinations.

Table 1
Quantities of crop residues as of 2022 (in millions of tons or Tg), and their content of elemental carbon (C), nitrogen (N), phosphorus (P) and potassium (K). Cereal residue production statistics are from Smerald et al. (2023). Data on carbon and nutrient composition are from Fu et al. (2021).

Geography	OURs	Dry biomass (Tg)	C (Tg)	N (Tg)	P (Tg)	K (Tg)
World	Rice straw	1343.6	54685	1061	2647	23379
	Wheat straw	1431.8	60279	36167	644	33576
	Maize stover	2914.5	127830	2915	2769	51674
China	Rice straw	204.9	8339	162	404	3565
	Wheat straw	138.8	5843	83	62	3255
	Maize stover	383.6	16825	384	364	6801
India	Rice straw	320.2	13032	253	631	5571
	Wheat straw	179.7	7565	108	81	4214
	Maize stover	88.6	3886	89	84	1571
USA	Rice straw	6.1	248	5	12	106
	Wheat straw	84.7	3566	2140	963	1986
	Maize stover	285.3	12513	285	271	5058
Brazil	Rice straw	11.2	456	9	22	195
	Wheat straw	18.7	787	11	8	439
	Maize stover	187.2	8211	187	178	3319
Kenya	Rice straw	0.2	8	0	0	3
	Wheat straw	0.7	29	0	0	16
	Maize stover	19.2	842	19	18	340

Table 2
Elemental quantities (tons) of poorly utilized nitrogen (N), phosphorus (P), and potassium (K), in livestock and human excreta, as of 2010, in selected countries and globally. Data on N, P and K are from Devault et al., 2025. Quantities of carbon (C) are estimated based on the estimated human and animal fecal production provided by Berendes et al. (2018), with the estimate of 5 % carbon for human feces taken from Snyder et al. (1975). No credible estimate of the percent carbon was found for livestock in general, so the 5 % was used as a rough estimate to calculate the amount of carbon in global livestock manure.

Geography	Excreta source	C (Tg. 2014)	N (Tg, 2010)	P (Tg, 2010)	K (Tg, 2010)
World	Human	40.5	20.63	2.82	6.10
	Livestock	156	16.17	1.29	24.77
China	Human	7.70	5.59	0.76	1.48
	Livestock	n.d.	2.28	0.11	2.59
India	Human	4.46	3.05	0.47	1.02
	Livestock	n.d.	4.75	0.24	8.54
USA	Human	2.47	1.34	0.15	0.37
	Livestock	n.d.	1.64	0.27	1.76
Brazil	Human	2.92	0.62	0.78	0.18
	Livestock	n.d.	0.92	0.11	1.31
Kenya	Human	n.d.	0.11	0.16	0.03
	Livestock	n.d.	0.04	0.00	0.08

(Moraes et al., 2021), but there are limits to this, and food systems produce a great deal of inedible by-products. Making use of inedible and wasted food is an obvious target for action toward circular food systems. This is not an easy challenge, however, and success has varied across contexts. Japan has been relatively successful in reducing food waste, with most municipalities providing financial support for household composting (Morais and Ishida, 2025). In contrast, food waste policies are inconsistent across the USA, often lacking enforcement or incentives (Ryen and Babbitt, 2022). For example, landfill bans for food waste have been ineffective at reducing landfilling of food waste in most states where they have been implemented (Anglou et al., 2024).

A World Bank study found that “food and green waste” (kitchen and landscape by-products) was the largest category of municipal solid waste (MSW), making up 44 % of global MSW (Kaza et al., 2018). Over two billion tons of MSW are produced annually, much of which goes to landfill (UNEP, 2024a). Nearly half the weight of landfilled waste is organic, with enormous production of methane and other GHGs (e.g., Wang et al., 2024). Indeed, 8–10 % of global anthropogenic GHG emissions are associated with food waste (UNEP, 2024b). Once organic materials are combined into a mixed-stream waste management process, they are likely compromised for many uses. Combined materials can be used for energy production through anaerobic digestion (e.g., Campuzano and Gonzalez-Martinez, 2016), and methane can even be recovered as landfilled organic materials break down, but this is not a “highest use” of those materials, and diverting organic matter from landfill is an urgent policy priority to reduce GHG production (Lair et al., 2024) and to increase bionutrient circularity.

Among the categories of food loss and waste, the highest levels are for fruits and vegetables (F&V), both proportionally and in terms of the overall mass and volume (FAO, 2021; UNEP, 2024b; Fabi et al., 2021). This is because they are the most perishable and because much of F&V mass is inherently inedible (peels, pits and similar). Food waste accounts for around half of the mass of total household waste globally, with 40 % of that being F&V waste (UNEP, 2024b). Such losses are higher in low- and middle-income countries, where refrigeration is less accessible. The relative wastage from each node of the food system varies across contexts (FAO, 2021), with implications for whether and how the organic resources may be utilized, and by whom. Although a minority of wastage occurs at food processing stages, processing by-products are most consolidated and thus most readily available for efficient industrial utilization. Most wastage occurs on small farms and in private kitchens and thus is inherently diffuse and difficult to recover.

As with waste management more broadly, alternatives for reducing food waste are considered as a hierarchy of options. In the food waste hierarchy, the highest option is to redesign the system to avoid unnecessary production (Papargyropoulou et al., 2014). A circularity strategy would ideally integrate reduction of surplus production, reduce losses through improved handling, and strategically utilize damaged or otherwise inedible products for producing feed, energy and soil amendments. For example, training farmers on improved harvest methods and enhancing access to storage and preservation technologies could be complemented by training on converting unmarketable products to valuable ones through complementary biological transformations as discussed below. Market development will also be necessary, for example to establish demand for insect-based feed made from food scraps. For inedible food wastes, industrial uses (reprocessing to extract valuable compounds for pharmaceuticals or cosmetics, for example) are the most valuable, followed by feeding animals, then by composting. From a hierarchical perspective, feeding insect larvae on vegetable peelings and spoiled fruit to produce animal feed would be a higher use than composting. The “up-cycle” from potentially wasted produce to insect-based feed may be more accessible in small-scale production systems than in larger ones, due to the high cost of industrial infrastructure. Similarly, regulatory innovation may be easier to implement in small economies than in larger ones (Pender et al., 2024).

2.3. *Human and animal excreta*

Food consumption results in the production of excreta, which are widely defined as wastes but were historically used for fertilizer. The human population exceeds 8 billion, and rears 1.7 billion cattle and buffaloes, 1 billion pigs, 2.2 billion sheep and goats, and 25 billion birds for food globally at a given time (Robinson et al., 2014; Dobermann et al., 2022). The quantities of nutrients in underutilized human and livestock excreta are significant; these resources could provide 16, 8 and 14 % of the N, P and K required by crops and grasslands worldwide, respectively (Devault et al., 2025). Of the world's fecal biomass associated with the food system, most is produced by livestock (79 %; Berendes et al., 2018). Both human and animal feces can carry disease, and both are significant resources if managed safely (Berendes et al., 2018). Nutrient recovery from manure and human excreta is a traditional practice that continues to varying extents around the world, and contemporary studies have confirmed that urine is an excellent fertilizer and a valuable source of plant nutrients (Larsen et al., 2021; Martin et al., 2022). While feces have to be carefully managed for both pathogens and nutrient availability, the nutrients in urine are present in plant-available form.

Most of the nutrients in excreta are wasted, however, and only a minority of excreta are safely managed. The global failure to productively manage excreta is catastrophic; billions of people lack access to safe sanitation, and the nutrients released into the aquatic environment fuel harmful algal blooms, anoxic conditions and other hazards. Inadequate sanitation and poor manure management harm food security through the negative effects of nutrient pollution, nutrient wastage, and by undermining gut health (Ngure et al., 2014). Fisheries are harmed when excess nutrients cause algal blooms while soils are depleted of those same nutrients. Diarrheal diseases that proliferate where sanitation is poorly developed prevent bodily utilization of nutrients that are consumed.

With rising interest in circularity, excreta are now increasingly seen as resources (Harder et al., 2020; van den Broek et al., 2024). Arguments in favor of recovering nutrients from excreta for agriculture include the considerable nutrient value of excreta, the economic and environmental costs of conventional wastewater treatment, and the harms associated with unmanaged excreta where sanitation services are absent or poorly developed (McKenna et al., 2023; Devault et al., 2025). Arguments against resource recovery from excreta might include respect for the pervasive distaste for the concept of linking food and excrement, the pathogen hazards associated with feces, the transition costs entailed, and the modest contribution that the nutrients in human excreta can make to meeting global fertilizer demand. While there are sociocultural barriers to the acceptance of fertilizers made from human excreta in most cultures, attitudes vary among cultural contexts, and there is evidence that perceptions can shift if the legitimate concerns about risks are addressed and the benefits are effectively communicated (Gwara et al., 2021; Pickering et al., 2024).

Resource-recovering sanitation provides an opportunity to recycle more of the nutrients and carbon in excreta to support food production while reducing nutrient pollution (Trimmer et al., 2017). A systems perspective calls for linking sanitation and agriculture to address sustainability of soil health and thus food production, as well as bodily food utilization through public health. Recovering nutrients and carbon is possible with conventional wastewater treatment (Achilleos et al., 2022; Kumar et al., 2017), and is already practiced to some extent. For example, the market for phosphorus recovery as struvite was valued at USD 1.42 billion in 2024 and is projected to reach USD 3.11 billion by 2033 (Growth Market Reports, 2024). As discussed below, biosolids from wastewater treatment are widely used for land application, but issues of contamination of biosolids are an increasing concern (e.g., Pozzebon and Seifert, 2023), likely incentivizing thermochemical transformations in the future.

Recovering nutrients and carbon from excreta would be easier, at least conceptually, if excreta were not mixed, diluted and contaminated. Container-based sanitation practices that allow separate collection of feces and urine, combined with low-tech strategies for nutrient recovery, can be viable as decentralized systems (Russel et al., 2019; World Bank Group, 2019). A global or even local transition from sewer-based sanitation to a source-separating, resource-recovering paradigm is acknowledged to be challenging given the massive societal investment in and acceptance of sewered sanitation. But only a minority of the world's population enjoys sewered sanitation, and globally, over 80 % of human excreta enter the environment without safe treatment (WHO/UNICEF, 2017; Baum et al., 2013). Practical non-sewered sanitation alternatives are emerging in some locations where sewered sanitation is out of reach, as in parts of Africa (Canova et al., 2025; Exton et al., 2025) and elsewhere, but also in locations where sewered sanitation is accessible, such as in Europe (Joveniaux et al., 2022; Simha et al., 2020; Söderholm et al., 2023).

Considerable innovation is ongoing to identify safe ways to recover nutrients and other valuable products from excreta (Harder et al., 2019; Rosemarin et al., 2020; Saliu et al., 2024; Lehmann et al., 2025). Methods for nutrient recovery from urine range from simple ("low-tech") options such as long-term storage (pH changes in stored urine eliminate pathogens) and alkaline dehydration (e.g., Simha et al., 2020), to more sophisticated ("high-tech") processes such as electrochemical stripping (Maurer et al., 2006) and membrane and filtration technologies. But the aspiration of nutrient recovery is far from mainstream, and implementing nutrient recovery from excreta is currently extremely limited. Below we note some of the materials and technical mechanisms that can be used to transform excreta into valuable products.

Treating human excreta as a resource can ideally incentivize the provision of sanitary services to the 3.5 billion people who lack access to safely managed sanitation. Considering excreta nutrients as a resource positions sanitation not as a societal burden, but as an opportunity to meet fertilizer demands. Human urine and feces contain most of the N, P, K and micronutrients in the foods people eat, in similar proportions to the nutrients generally required by plants. While the total nutrient value in human excreta represents only a modest proportion of the agricultural nutrients applied in high-income countries (particularly those that export large amounts of agricultural products, such as the USA), the agricultural use of nutrients in human excreta in regions such as Sub-Saharan Africa, where often insufficient quantities of nutrients are applied, could significantly improve the soil nutrient balances and boost yields (McKenna et al., 2023). Indeed, many African countries (and a third of countries globally) have more nutrients in human excreta than they import and use in fertilizers (Devault et al., 2025).

The livestock sector is a major source of nutrient waste and GHG emissions, and thus also provides opportunities for improving the bionutrient circularity of the food system (e.g., Espinosa-Marrón et al., 2022). While livestock are currently fed more than a third of the world's cereal harvest and a quarter of all roots/tubers and legume grain (Dobermann et al., 2022), livestock feed has the potential to transition to food system by-products and forages (van Zanten et al., 2019). Global livestock systems now produce a third of anthropogenic nitrogen emissions (including potent GHGs and pollutants; Dobermann et al., 2022). Livestock can be especially polluting in places like the United States where animal and plant agriculture have been spatially decoupled, making it difficult to recover the nutrients from livestock excreta to support crop nutrition.

While tremendous benefits could accrue from reconnecting livestock and crop production in circular nutrient cycles (Spiegal et al., 2020), feasibility is influenced by the transportation costs entailed. These costs in turn depend on the spatial relationship between the sources of the material (people, livestock) and the sinks that can receive it (agriculture), and the form in which the material is transported (whether it has been processed to reduce water content and enrich nutrients). Trimmer and Guest (2018) conducted an analysis of 56 cities around the world, looking at the distance between urban areas (sources of human bionutrients) and agricultural production (sinks for nutrients). They found that the three cities with the highest travel distances are in the USA, while in India, Nigeria, Uganda, and China, substantial crop production areas are located near densely populated areas. A more granular analysis supported the conclusion that the simplest approach to nutrient recovery to support food production (e.g., direct application of aged urine) is the most accessible approach in many of the places where nutrients are most needed (Echevarria et al., 2021).

Using excreta for fertilizer is a traditional practice in many parts of the world, but it has been eclipsed by synthetic fertilizers in recent decades. Considering contemporary crises related to climate change, conflict, fertilizer prices, sanitation and health, there is renewed interest in resource recovery from sanitation, both in low-income and in high-income settings (Joveniaux et al., 2022). While there is sociocultural resistance to the idea of eating food that has been fertilized with excreta, several studies have shown that food producers and consumers can accept excreta-based fertilizers if they are aware of the many benefits and their safety concerns are addressed (e.g., Gwara et al., 2021). Below, we consider the ways in which excreta, together with other OURs, can be utilized within a circular bionutrient economy. We acknowledge that there are enormous socio-cultural, regulatory and operational barriers to be overcome even if effective technical solutions emerge to support a transition to greater circularity for excreta-derived nutrients.

3. Transformation processes

For carbon and nutrients to be returned to the food system, OURs must be transformed in various ways. We consider three broad classes of material transformation processes: biological, thermochemical and physical. These three processes can be combined in sequence, and their products can also be combined.

3.1. Biological transformations

Biological transformation processes include physical and biochemical changes produced by diverse groups of organisms such as microbes, fungi, microfauna, worms, insects, livestock, algae and plants. These organisms transform otherwise inedible or discarded materials to produce food, feed, soil amendments and energy. Microbes play key roles in several biological transformations that are critical to CBE, including composting, anaerobic digestion and fermentation. Insects and livestock are also important in biological transformations in the food system. Algae can be grown on urine-based media to be used for energy, feed or fertilizer (reviewed by Tao et al., 2022).

Aerobic composting (including vermicomposting) and anaerobic digestion are the most common avenues to recovering nutrients from OURs. They can be conducted effectively at a wide range of scales, from household to farm and municipal scales. Composting technologies range from extremely simple to highly sophisticated, varying in scale and degree of process control. Composting is widely practiced on a commercial basis (Saqib and Sadef, 2025). Composting inevitably produces CO_2 as microbes break down organic materials, and can also produce the more powerful GHGs nitrous oxide (N_2O) and/or methane (CH_4) under certain conditions. The inclusion of biochar in the composting process can reduce GHG production and improve process efficiency and product quality, as discussed below. Process monitoring through sensor technologies can help avoid undesirable conditions, such as oxygen deficit. Oxygen-reduced environments select for methanogenic microbes, which is undesirable in most composting arrangements but deliberately achieved in anaerobic digestion, when the methane is captured as an energy source. Following anaerobic digestion, the residual material can be used as a soil amendment or further processed into compost and/or biochar (Abdullahi et al., 2008).

Energy is already widely produced from food waste, excreta, and crop residues, and there is tremendous potential to make better use of the nutrients in digestate. Marconi and Rosa (2024) contend that substituting nitrogen from anaerobic digestion in place of synthetic nitrogen has the potential to feed 2.5 billion people and decrease annual GHG emissions from the production and use of nitrogenous fertilizers by 70 %. Co-digestion of crop residues and livestock manure offers advantages in the production of renewable energy (Adnane et al., 2024), as does co-digestion of sewage sludge with other organic materials such as food waste (Li et al., 2024). Anaerobic digestion does not substantially reduce the mass or volume of the material, so the spatial relationships between digestate production sites and crops will determine whether transport costs are prohibitive. As noted below, pyrolysis reduces weight and volume and can be combined in some processes to concentrate nutrients from digestate.

It has also been argued that farm animals can play key roles in circular food systems as livestock can be fed on food scraps unfit for human consumption and forages grown on land unfit for annual crops (van Zanten et al., 2019). Indeed, the traditional role of pigs in Asia and elsewhere has been to recycle inedible materials, including excreta. Insects have recently emerged in this niche at both small and large scales, converting food waste and excreta into animal feed. Several insect species have been used to upcycle organic wastes, most notably housefly (*Musca domestica*; Cheng et al., 2021), mealworm (*Tenebrio molitor*; Moruzzo et al., 2021), house cricket (*Acheta domesticus*; Lundy and Parrella, 2015), and the black soldier fly (BSF, *Hermetia illucens;* Vilela et al., 2021). Insect cultivation provides an opportunity to address the increasing global demand for animal protein while reducing waste and the pressures on both aquatic and terrestrial resources (Raman et al., 2022). The insects' frass and other residues can be used as a soil amendment, significantly improving soil health, crop yield and nutritional quality of crops (Anyega et al., 2021). BSF is the most widely cultivated insect, efficiently transforming organic wastes such as food scraps and excreta into larval biomass. The dry weight of BSF larvae can contain up to 35 % lipids and 50 % protein (Caruso et al., 2014), with a favorable amino acid profile for animal feeds (Elwert et al., 2010; van Huis, 2015), though the nutritional quality of the output feed depends upon the quality of the input feedstocks. As further discussed below, contaminants are a concern for CBE; if feedstocks are contaminated with heavy metals or other toxins, there is potential for bioaccumulation in larvae and frass (Addeo et al., 2024). Even if technical hurdles can be cleared, public perception and the absence of supportive regulatory frameworks remain obstacles (Doughty et al., 2024).

3.2. Thermochemical transformation

A variety of methods utilize heat to transform materials for various purposes, including the production of biofuels and soil amendments. Several different thermal processes are used for managing biosolids, for example (Werther and Ogada, 1999), including incineration and pyrolysis, with the former currently used more widely. However, among the processes and products of thermochemical transformation, pyrolysis has received the most attention in recent literature (Paudel et al., 2024) and will be the focus here. Pyrolysis, the high-temperature treatment of organic materials in a low-oxygen environment, is used to transform organic materials into biochar, a carbonaceous material that can persist in soils for hundreds of years and can provide numerous benefits to soil health (Lehmann and Joseph, 2024). Pyrolysis transforms about half of the carbon in the feedstock into persistent carbon in biochar.

When used as a soil amendment, biochar generally improves crop production, with an average yield increase of 20–26 % across published studies, depending on soil-biochar interactions (Ye et al., 2020; Bekchanova et al., 2024). Biochar enhances water-holding capacity and reduces soil acidification (Gao and Masiello, 2024; Lehmann et al., 2011). Since it has a higher cation retention capacity than any other soil amendment or soil organic matter (Liang et al., 2006), biochar can adsorb cationic nutrients and release them slowly. Biochar enriched with nutrients (e.g., from urine) can serve as a soil amendment that increases soil fertility (Schmidt et al., 2017). Synergies with food waste and excreta can be achieved by blending nutrients from these nitrogen-rich materials with carbon-rich biochar. Composting with biochar enhances composting speed and quality (Antonangelo et al., 2021).

Biochar can be produced from a wide variety of organic materials, including OURs such as weeds and other landscape trimmings, crop residues, manure or manure-byproducts, and biosolids. Pyrolysis of crop residues can be beneficial by increasing the persistence of carbon returned to soil. While crop residues are often left on fields to protect soils and return carbon and nutrients to soil, maize stover, for example, is rapidly broken down and metabolized, so its contribution to soil organic matter is transient. Yang et al. (2017) showed that maize stover biochar was superior to the incorporation of non-pyrolyzed stover or a conventional fertilizer control in terms of GHG release (CO_2, N_2O and CH_4) and benefits to soil health. Pyrolyzing a portion of crop residues may be a higher use than microbial decomposition in the field. Additionally, pyrolizing biosolids has the potential to reduce bulk, mass and organic pollutant content, with the possibility of using the biochar as a soil amendment or other purpose (e.g., capturing contaminants in landfill leachate or as building material). Bones are a major waste product of the livestock industry (analogous to vegetable peels as a part of “food waste”); bones can be pyrolyzed to produce bone char that can be used as an alternative source of bioavailable phosphorus for crop production (Ahmed et al., 2021), as is practiced on a modest scale in Ethiopia (Simons et al., 2023).

Biochar can be produced at a range of scales, using technologies that range from a pit or trench in the ground to systems based on sophisticated process engineering. Even simple flame-curtain kilns (e.g., “Kon-Tiki” kilns) can be used to produce high quality biochar with low emissions (e.g., Cornelissen et al., 2016). Because biochar can serve as a long-term carbon sink (as established by IPCC; Woolf et al., 2021), there is potential for carbon markets to catalyze large-scale production of biochar and its use to capture carbon and improve the health and water-holding capacity of agricultural soils (Lehmann et al., 2021). The carbon market has started to function in Africa and southeast Asia (e.g., George, 2024), enabling smallholder farmers to access funding and technical support for in-field pyrolysis of crop residues, although the scale is limited to date (Solidaridad Network, 2023). The simple technology needed to produce biochar, combined with its growing market potential as a soil amendment and within carbon markets, makes it an increasingly accessible and profitable way for smallholders to improve their soil health and food security. Profitable production at larger scales generally entails ready access to large-scale inputs (e.g., through co-localization with a processing plant generating agroindustrial by-products), the use of pyrolysis by-products (syngas, bio-oil, and/or heat), and carbon credits.

3.3. *Physical and physiochemical transformations*

The challenge of valorizing OURs can be addressed by a wide range of physical and chemical processes that convert low-value (or negatively valued) materials to higher value products. For example, with industrial processing and formulation, excreta-based fertilizers can be light, uniform, with defined or even bespoke nutrient profiles and without undesirable sensory characteristics (Lehmann et al., 2025). Relevant physical processes include chopping, drying, and pelleting. Physiochemical transformations include stripping, adsorption, electrochemical treatments and precipitation.

Chopping enhances drying, and drying can increase shelf life and enable subsequent operations such as pyrolysis. Thermal processes can be used to pasteurize or sterilize. Extruding and pellating biomass can enhance biomass uniformity, with benefits for downstream processes such as pyrolysis. The field of food science may be a source of relevant physical and physiochemical technologies, as it employs a powerful toolkit for physical transformation of foodstuffs that can be applied to OURs in various ways to improve their quality, safety, stability, appearance and utility. While these processes are already being used to reduce food waste, there is scope to increase their applications in a circular food system.

4. Interconnected pathways to circularity

The three transformation mechanisms discussed above (physicochemical, biological and thermochemical) can be applied to various OURs, leading to complex, interacting pathways that can fruitfully connect in various ways that do not resemble simple circles (Fig. 1b). Approximately 40 % of the world’s arable land is dedicated to producing livestock feed (Mottet et al., 2017), and 35 % of crop calories are fed to livestock (Berners-Lee et al., 2018). Insect-based feeds produced from food scraps offer a way to reduce that burden on nature. Another option for designing out the waste associated with livestock is dietary change toward reducing excessive meat consumption. Reducing beef consumption in particular could reduce many of the harms associated with contemporary food systems, including GHGs and land use/deforestation (Godfray et al., 2018; Xu et al., 2021), as well as providing health benefits. This has implications for crop production and thus crop residues, since direct consumption of plant-based foods is more efficient than consumption of meat: reducing meat consumption would reduce production of feed grains, altering availability of crop residues and the dynamics of circularity pathways. Reducing the flow of plant-based materials from the food system to biofuels will likewise influence residue availability.

All three of the resources discussed above (crop residues, food scraps and excreta) can be digested to produce energy or composted to produce valuable soil amendments. Indeed, these OURs are best co-digested or co-composted, with their residues used to improve soils. Cereal residues are high in carbon, so combining them with food waste and/or excreta (higher in nitrogen) can help achieve the balance between carbon and nitrogen needed for efficient microbial degradation. Urine is an excellent source of nitrogen for composting cereal residues and for producing nutrient-charged biochar for use as a soil amendment (Krounbi et al., 2021). Mixed excreta (including feces, which are of high concern for pathogens) can be safely composted if the process is managed in a way that allows high composting temperatures to be reached (Werner et al., 2023).

Biochar has been reported to benefit a range of biological transformations involved in CBE pathways, including composting, anaerobic digestion and BSF production. When biochar is a component of a composting process, the rate of decomposition is higher, and the resulting compost product is superior in nutrient content (Nguyen et al., 2022). The inclusion of biochar in the composting process also results in lower greenhouse gas emissions (Yin et al., 2021). Biochar enhances anaerobic digestion of sewage sludge (Devi and Eskicioglu, 2024) and food waste (Ambaye et al., 2021). Hoang et al. (2022) reviewed the physical, chemical and biological mechanisms by which biochar improves the process of anaerobic digestion, which include the favorable microporous living environment for bacteria, buffering capacity and electrical conductivity, and adsorption of toxic compounds that inhibit microbial growth and metabolism. Other reviews of microbial responses to biochar in soil and anaerobic digestion reactions have also noted that biochar increases microbial abundance and diversity as well as carbon- and nutrient-cycling functions (Kerner et al., 2023; Zhao et al., 2024). Biochar’s porous structure provides microbial habitat, enhances nutrient and water retention, and reduces the effects of toxins.

The inclusion of biochar in the material fed to BSF can improve larval survival and growth, reduce greenhouse gas (N_2O) and ammonia (NH_3) emissions, and improve nitrogen, potassium and phosphorus content of the frass/residue (Beesigamukama et al., 2020; Akumah et al., 2021). BSF frass can be included with compost and biochar as part of a high-value soil amendment (e.g., Tan et al., 2021), and inclusion of biochar in BSF rations presumably leads to a more valuable frass as well. The residues from BSF production include the chitinous exoskeletons that are shed during insect development. This material can be used directly as part of a soil amendment or pyrolyzed to produce a biochar with beneficial effects on plants and soil organisms (Bulak et al., 2023). Particularly when BSF are fed on human excreta, such as fecal material from source-separating toilets (Banks et al., 2014), thermochemical treatment (i.e., pasteurization) may be desirable to allay hygiene concerns. BSF residues produced on human feces (frass and other remaining material after the larvae are harvested) can be used to produce a high-quality biochar that is high in phosphorus and free of pathogens (Nkomo et al., 2021).

Strategically interconnecting transformation pathways for the three main resources described here—crop residues, food scraps and excreta—can ensure that carbon and nutrients are retained in food, feed, soil and other growing media and are either available for crop production or sequestered as soil organic matter. Building and strengthening these connections must be considered as the circular bionutrient economy progresses. The effect of biochar on enhancing biological processes that transform underutilized resources through composting, anaerobic digestion and insect culture is an opportunity to improve process efficiency and effectiveness. The potential of pyrolysis for destroying contaminants, and potential of biochar for immobilizing soil contaminants, must be taken seriously as societies reckon with the vast quantities of organic pollutants and heavy metals that are regularly deposited in agricultural soils (NASEM, 2024). This will require that the scope of food policy analysis subsume a broad range of issues, from sanitation to soil health to co-localization of industries and enterprises that produce and utilize nutrients.

5. Challenges, tradeoffs and risks associated with circular bionutrient economies

The pathways to CBE offer compelling environmental and resource security benefits, but require navigating complex challenges, risks and tradeoffs. Challenges include technical, regulatory, and operational issues, as well as formidable sociocultural obstacles. Wasted materials can be viewed as disgusting; food waste can be stigmatized, and excreta are subject to deep taboos that constrain the collection and use of this resource. These negative cultural associations are both emotional and rational, as wastes have repulsive sensory features and can be linked with the spread of disease. Shifting norms will require changes in perception of value and responsibility, and the reduction in stigma will likely be a slow process requiring investment in exposure and education. A transition to CBE and a circular economy more broadly will require a general shift from a mindset of hygienic extractionism to one of thrifty stewardship. The needed investments in innovation come with financial risks, and the processes can entail risks to the health of soils and people. Here we highlight two categories of jeopardy associated with pathways to CBE: economic risks and potential contamination hazards.

Transitions to CBE require novel perspectives, infrastructure, capabilities, and policies. These can be costly and investments must be made with consideration for economic tradeoffs, such as those between cost competitiveness and environmental benefits. Sophisticated processing methods may ensure “clean” (less polluting), safe, and standardized products, but are costly to establish. Any investment in CBE cannot be recovered unless nutrient recovery technologies are cost-competitive with conventional fertilizers, which may not be possible without subsidies or carbon credits when the environmental costs of the status quo are externalized. The cost of transporting bulky organic residues can rapidly exceed the value of the products, so not all resources are recoverable without decentralization and strategic co-localization of infrastructure, but economies of scale and other efficiencies are more difficult to achieve in decentralized systems. Recovering nutrients and carbon from sanitation by-products means dealing with chemical and biological hazards that may contaminate land and food, and quality control may be sacrificed in highly decentralized systems.

While sophistication in OURs processing may offer advantages, these may not overcome the costs entailed. Adding steps reduced techno-economic viability of pyrolysis of rice and wheat residues in India (Bhatnagar et al., 2022). Similarly, in the case of urine-derived fertilizers in Uganda, the simplest approach was found to be economically viable, while the costs and energy requirements of producing a more sophisticated fertilizer product from stored urine were found to exceed the economic value (Lohman et al., 2020). Many options can be considered in such analyses, and what works may or may not be revealed through a technoeconomic assessment made under a given set of assumptions. The most appropriate approach will be context-dependent, and drivers such as technology options, availability of investment capital, and regulations are likely to evolve over time, shifting the landscape of viability.

Contaminants pose another set of risks for CBE. Soil health is compromised when nutrients and organic matter are returned to soils via materials contaminated with persistent pollutants, such as heavy metals, per- and polyfluorinated alkyl substances (PFAS), microplastics, pharmaceuticals, etc. On the other hand, organic materials such as compost and biochar can be part of the solution to soil contamination. Composting can degrade organic contaminants, and compost can be used to immobilize heavy metals and other toxins (Huang et al., 2016; Kästner and Miltner, 2016). As discussed below, the process of pyrolysis can destroy organic pollutants (Krahn et al., 2023; Sørmo et al., 2024), and biochar can bind and immobilize contaminants in soils (Wu et al., 2017; Yuan et al., 2019), making it particularly promising as a soil additive for remediation of contaminated soils.

Compost can be used to remediate soil contamination, but compost may also carry heavy metals, PFAS and/or other chemical or biological contaminant(s) (Farrell and Jones, 2009). A major source of PFAS in compost in some contexts is food service materials that are made from paper and other compostable materials that are coated to make them impermeable to water and grease (Timshina et al., 2024). Food scraps can also carry fluorinated compounds, such as pesticide residues, and compost made from household food waste can carry these chemicals (van Asselt et al., 2023). Increasing numbers of pesticides are fluorinated to increase their stability in the environment, and additional PFAS may come from the “inert ingredients” (e.g., adjuvants) included in pesticide formulations as well the leached materials from container linings (Donley et al., 2024).

Biochar made from biosolids can immobilize lead in contaminated soils (Netherway et al., 2019), but biosolids may also contain heavy metals, PFAS and other persistent contaminants (Marchuk et al., 2023), with the species and concentrations of contaminants varying across contexts. Even source-separated human and animal excreta may carry pharmaceutical residues and pathogens (van der Fels-Klerx et al., 2024). Contaminated soils may lead to contaminated foods, depending on the extent of transfer of compounds of concern from soil to the edible portion of the crop (van der Fels-Klerx et al., 2024). People may also be exposed to contaminated soil through exposure to dust and water. Food production can be compromised when pesticides are returned to soils with contaminated manure; for example, chicken feed contaminated with glyphosate led to residues in manure that was used to fertilize vegetables, leading to reduced yields (Muola et al., 2021).

Many food system contaminants have the potential to bioaccumulate in circular food systems. To assess food safety concerns associated with circular food systems, van der Fels-Klerx et al. (2024) developed a framework to prioritize possible hazards. They used this framework to assess several case studies, including the risks associated with BSF larvae when grown on animal excreta and food waste and then used as animal feed. Considering the occurrence of various chemical contaminants, their accumulation in the insects, and the severity of the consequences of human exposure, the authors considered veterinary drugs, pesticides and mycotoxins to be low priority concerns, dioxins and PCBs to be intermediate priority concerns, and heavy metals (cadmium and lead) to be high-priority concerns.

Both the benefits and risks associated with CBE are striking and imply the need for regulatory guidance, accessible analytical methods, and incentives to propel positive change while managing the potential hazards that could derail further progress. For example, BSF production can enable productive use of food waste and excreta, but there is a need to effectively manage BSF nutrition to ensure safety of animal feed and animal-source foods that people eat. As discussed above, composting and pyrolysis can destroy organic pollutants, and their products can also bind and immobilize toxic compounds and elements, with pyrolysis and biochar being the most potent.

6. Policy implications

Effective CBE implementation requires not only technical innovations, but also socio-economic transformations, including supportive policies, new business models and institutional arrangements that reflect the economic and spatial realities of OURs. Many policies affecting food systems are designed to support the prevailing linear economy, such as fertilizer subsidies, regulations preventing the upcycling of food waste, and many sanitary regulations. These policies have the unintended effect of adversely affecting efforts to implement CBE. Many African governments invest in fertilizer subsidies to support crop production and food security (e.g., Benson et al., 2024); a shift to supporting CBE would, in principle, be a more financially and environmentally sustainable approach to achieving these aims, while advancing sanitation goals as well. Revisiting food policy frameworks and specifics to adapt them to CBE will require evidence, investment and advocacy.

Regulatory policies will need to be adapted to support rather than impede bionutrient circularity while safeguarding public health from microbial and chemical hazards. Increasing attention is being paid to the chemical contaminants associated with the land application of municipal biosolids, which has been justified as a way of enhancing soil organic matter. While biosolids are known to carry a range of contaminants, including "forever chemicals" (PFAS), regulatory policy has been slow to protect soil health and the food system from these contaminants (Popoola et al., 2023). Source-separating sanitation is one approach to avoiding the contamination of excreta that will be used as a soil amendment. Institutional contexts may, however, inhibit the implementation of innovations like source-separating sanitary technology (Beal et al., 2020).

Certification and standardization can be important for market development (Lehmann et al., 2025). Adequate regulatory frameworks governing the use of biochar, or the use of insect larvae for feed, may also be absent or sufficiently underdeveloped in many contexts, such that it is risky for investors to establish the necessary infrastructure to develop new value chains. Limited knowledge and awareness of the benefits of novel fertilizers and soil amendments, potential concerns about quality and value, together with the absence of meaningful and enforced standards, means that buyers may lack confidence in the products and sellers are not able to command the prices they may need for economic viability, particularly when conventional fertilizers are subsidized.

Considering the relatively low value density of OURs, decentralized business models can better support the utilization of spatially diffuse OURs originating from farms, kitchens and toilets because of the high transportation costs required for centralized processing. For example, decentralized pyrolysis of rice and wheat residues with minimal processing was found to show better economic and environmental performance than more centralized approaches in India (Bhatnagar et al., 2022). Decentralized composting systems can reduce transport distances, but may struggle to sustain stable and adequate processing conditions (Arrigoni et al., 2018). Optimization analysis can be used to determine the most efficient level of decentralization, as in the case of pyrolysis of poultry manure (Zhao et al., 2020; Bora et al., 2020).

The scale at which organic circularity is optimally practiced will depend on the resources of interest, the magnitude and concentration of the resource, and the technology required to add value to it through the transformation pathways considered above. As depicted in Fig. 2, resources from small farms and households (even in cities) are inherently diffuse, as they are produced in small quantities and managed by vast numbers of individuals. Small-scale producers are likely best able to use the OURs from their own farms for composting and pyrolysis. On-farm organic resources are likely needed to maintain soil health locally and may be too diffuse to be efficiently sourced by other enterprises. Small- to medium-scale enterprises (SMEs) may be more effective at tapping the byproducts produced by markets, processors, and sanitation providers. These SMEs can serve as critical intermediaries in scaling CBE by bridging the gap between diffuse resource generation and both diffuse and concentrated agricultural demand.

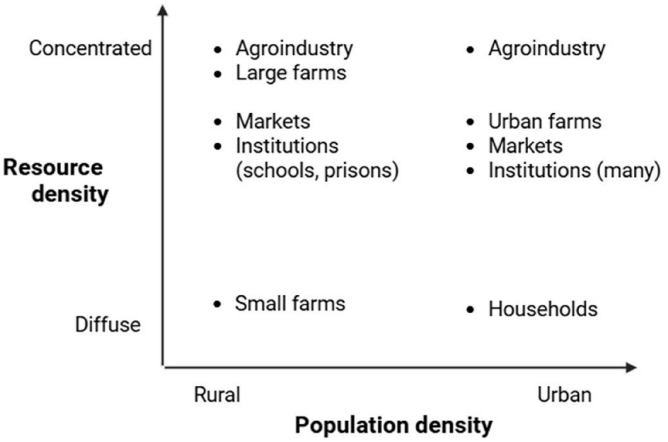

Fig. 2. A framework for considering possible sources of organic underutilized resources, partitioned by axes of concentration and degree of urbanization.

Designing effective CBE strategies thus requires coordinated action across actors and scales. Investments in training, financing, and market access should complement technology development, which can further enable both on-farm adoption and SME-led enterprise models. Meanwhile, governments and nonprofits have a role to play in shaping regulatory environments. Clear standards, safety guidelines, and quality assurance mechanisms are essential to de-risk private investment and build trust in emerging markets for biochar, excreta-based fertilizers, and insect-derived feeds.

7. Conclusions

We propose synergistic pathways through which nutrient circularity in the food system can contribute to reducing greenhouse gas emissions associated with agriculture, improving and maintaining agricultural productivity in the face of climate change through soil restoration, reducing the pollution of water, aquatic and terrestrial environments, and enhancing ecosystem services. CBE allows for the transformation of multiple, complementary organic by-products into fertilizers and feeds, potentially offsetting the financial and environmental costs of conventional waste management and agricultural inputs, and providing livelihoods based on agricultural enterprises that create and utilize these products. For example, a sanitation company collecting excreta can generate value from the resource rather than paying a tipping fee to dispose of it. The use of the excreta-derived fertilizer reduces the need to use fertilizers made from petrochemicals, offsetting the carbon footprint associated with the latter. Building soil organic matter sequesters carbon where it is most needed, and this sequestration is durable in the case of biochar. Circular animal feed production can potentially reduce feed costs while reducing the pressure on the land and fisheries from which feed ingredients are sourced.

This paper advances the circular economy literature by exploring synergies among transformation mechanisms and pathways that can keep in use the nutrients and carbon in three dominant by-products of the food system. Food systems inevitably produce enormous volumes of crop residues, inedible food scraps and excreta, which have complementary carbon-to-nitrogen ratios. The vast amounts of these underutilized materials can be returned to the food system through synergistic combinations of biological, physical and thermochemical transformations. While many reports focus on single waste streams or technologies, this paper highlights synergies that can be achieved when food system by-products are strategically co-processed. Through intersecting pathways employing composting and anaerobic digestion and other biological transformations, physical processing and pyrolysis, the nutrients and carbon in OURs can be converted to feed, soil amendments and other valuable products rather than released into the environment as pollutants. The way this is implemented will vary across contexts, likely with a blend of industrial operations at food system nodes where large volumes of OURs are available (e.g., processing plants) and smaller-scale, decentralized systems addressing more diffuse by-products. The distribution of costs and benefits will vary with these system architectures, with some available evidence for major benefits of decentralized resource recovery in low-resource, high population areas like informal settlements (World Bank Group, 2019).

As with many issues of concern to the environment and public health, transforming the food system for circularity involves shifts in public perception and motivation, as well as careful management of tradeoffs related to time frames and lags (e.g., immediate costs and longer-term benefits); investors and beneficiaries (e.g., who gains and who bears costs and environmental burdens; private investment and public welfare); and economic feasibility (transition costs and price points). Dealing with repulsive and potentially hazardous materials like excreta and food waste can create harm and resistance unless managed safely, equitably and respectfully to create opportunities rather than additional layers of disparity. The investments required for the development and optimization of a new generation of equipment and machinery, as well as the larger systems changes, are expensive and present risks and challenges. Depending on the economic, environmental and social context, the transition will require different blends of private entrepreneurial and philanthropic investment and public investment aimed at benefiting environmental integrity, public health, and adaptation to climate change.

Where resources are or can be aggregated and conditions enable and incentivize the development of advanced infrastructure, sophisticated approaches to nutrient recovery may be viable. Where OURs are more diffuse and financial resources are more constrained, simpler and more decentralized approaches are likely to be more accessible. A successful CBE will likely entail a blended system architecture that includes centralized facilities to enable efficiencies, with decentralized components that benefit a wider set of local stakeholders. Because communities currently lacking adequate access to sanitation and fertilizer are less “locked in” to wasteful norms, they tend to be more innovative and receptive to novel CBE opportunities but are also perhaps more vulnerable to exploitative and unsafe arrangements. Navigating the synergistic pathways to circular bionutrient economies can provide compelling benefits and co-benefits, with progress along these pathways requiring incentives, support and integration of technical, sociocultural, legal-regulatory, and business innovations, and careful attention to equity outcomes. Transitioning to CBE further requires acknowledging and navigating tradeoffs and challenges to establish linked value chains that will vary by context.

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CRediT authorship contribution statement

Rebecca Nelson: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Visualization, Writing – original draft, Writing – review & editing. **Jensen Njagi:** Data curation, Investigation, Writing – original draft. **Isabella Culotta:** Conceptualization, Investigation, Writing – original draft. **Eli Newell:** Conceptualization, Visualization, Writing – review & editing. **Shuai Zhou:** Data curation. **Krisztina Mosdossy:** Writing – original draft. **Erick Abala:** Conceptualization. **Chuan Liao:** Conceptualization, Writing – review & editing. **Johannes Lehmann:** Conceptualization, Writing – review & editing. **Charles Midega:** Conceptualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare no conflicts of interest.

Data availability

No data was used for the research described in the article.

References

Abdullahi, Y., Akunna, J., White, N., Hallett, P., Wheatley, R., 2008. Investigating the effects of anaerobic and aerobic post-treatment on quality and stability of organic fraction of municipal solid waste as soil amendment. Bioresour. Technol. 99 (18), 8631–8636. https://doi.org/10.1016/j.biortech.2008.04.027.

Achilleos, P., Roberts, K.R., Williams, I.D., 2022. Struvite precipitation within wastewater treatment: a problem or a circular economy opportunity? Heliyon 8 (7), e09862. https://doi.org/10.1016/j.heliyon.2022.e09862. PMID: 35874052; PMCID: PMC9304724.

Addeo, N.F., Scivicco, M., Vozzo, S., Bovera, F., Asiry, K.A., Alqurashi, S., Cacciola, N.A., Severino, L., 2024. Mineral profile and heavy metals bioaccumulation in black soldier fly (*Hermetia illucens*, L.) larvae and frass across diverse organic substrates. Ital. J. Anim. Sci. 23 (1), 179–188. https://doi.org/10.1080/1828051X.2024.2302845.

Adnane, I., Taoumi, H., Elouahabi, A., Lahrech, K., Oulmekki, A., 2024. Valorization of crop residues and animal wastes: anaerobic co-digestion technology. Heliyon 10 (5), 326440.

Ahmed, M., Nigussie, A., Addisu, S., Belay, B., Lehmann, J., Sato, S., 2021. Valorization of animal bone waste for agricultural use through biomass co-pyrolysis and bioaugmentation. Biomass Convers. Biorefinery 1–10.

Akumah, A.M., Nartey, E.K., Ofosu-Budu, G.K., Ewusie, E.A., Offei, B.K., Adamtey, N., 2021. Innovations in market crop waste compost production: use of black soldier fly larvae and biochar. Int. J. Recycl. Org. Waste Agric. 10 (2), 185.

Almaraz, M., Kuempel, C.D., Salter, A.M., Halpern, B.S., 2022. The impact of excessive protein consumption on human wastewater nitrogen loading of US waters. Front. Ecol. Environ. 20 (8), 452–458. https://doi.org/10.1002/fee.2531.

Ambaye, T.G., Rene, E.R., Nizami, A.S., Dupont, C., Vaccari, M., van Hullebusch, E.D., 2021. Beneficial role of biochar addition on the anaerobic digestion of food waste: a systematic and critical review of the operational parameters and mechanisms. J. Environ. Manag. 290, 112537.

Anglou, F.Z., Sanders, R.E., Stamatopoulos, I., 2024. Of the first five US states with food waste bans, Massachusetts alone has reduced landfill waste. Science 385 (6714), 1236–1240. https://doi.org/10.1126/science.adn4216.

Antonangelo, J.A., Sun, X., Zhang, H., 2021. The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. J. Environ. Manag. 277, 111443.

Anyega, A.O., Korir, N.K., Beesigamukama, D., Changeh, G.J., Nkoba, K., Subramanian, S., van Loon, J.J.A., Dicke, M., Tanga, C.M., 2021. Black soldier fly-composted organic fertilizer enhances growth, yield, and nutrient quality of three key vegetable crops in sub-Saharan Africa. Front. Plant Sci. 12, 680312. https://doi.org/10.3389/fpls.2021.680312.

Arrigoni, J.P., Paladino, G., Garibaldi, L.A., Laos, F., 2018. Inside the small-scale composting of kitchen and garden wastes: thermal performance and stratification effect in vertical compost bins. Waste Manag. 76, 284–293.

Banks, I.J., Gibson, W.T., Cameron, M.M., 2014. Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation. Trop. Med. Int. Health 19, 14–22.

Baum, R., Luh, J., Bartram, J., 2013. A global estimate of sewerage connections without treatment and the resulting impact on MDG progress. Environ. Sci. Technol. 47 (4), 1994–2000. https://doi.org/10.1021/es304284f.

Beal, C., Fam, D., Clegg, S., 2020. Over-promising and under-delivering: institutional and social networks influencing the emergence of urine diversion systems in Queensland, Australia. In: Interdisciplinary and Transdisciplinary Failures. Routledge, pp. 78–94.

Beesigamukama, D., Mochoge, B., Korir, N.K., Fiaboe, K.K., Nakimbugwe, D., Khamis, F. M., et al., 2020. Biochar and gypsum amendment of agro-industrial waste for enhanced black soldier fly larval biomass and quality frass fertilizer. PLoS One 15 (8), e0238154.

Bekchanova, M., Campion, L., Bruns, S., Kuppens, T., Lehmann, J., Jozefczak, M., Cuypers, A., Malina, R., 2024. Biochar improves the nutrient cycle in sandy-textured soils and increases crop yield: a systematic review. Environ. Evid. 13, 3.

Benson, T., De Weerdt, J., Duchoslav, J., Masanjala, W., 2024. Fertilizer Subsidies in Malawi: from past to Present. MaSSP Working Paper 44. International Food Policy Research Institute, Washington, DC.

Berendes, D.M., Yang, P.J., Lai, A., Hu, D., Brown, J., 2018. Estimation of global recoverable human and animal faecal biomass. Nat. Sustain. 1 (11), 679–685.

Berners-Lee, M., Kennelly, C., Watson, R., Hewitt, C.N., 2018. Current global food production is sufficient to meet human nutritional needs in 2050 provided there is radical societal adaptation. Elem Sci. Anth. 6, 52.

Bhatnagar, A., Khatri, P., Krzywonos, M., Tolvanen, H., Konttinen, J., 2022. Techno-economic and environmental assessment of decentralized pyrolysis for crop residue management: rice and wheat cultivation system in India. J. Clean. Prod. 367, 132998.

Bhuvaneshwari, S., Hettiarachchi, H., Meegoda, J.N., 2019. Crop residue burning in India: policy challenges and potential solutions. Int. J. Environ. Res. Publ. Health 16 (5), 832.

Bora, R., Tao, Y., Lehmann, J., Tester, J., Richardson, R., You, F., 2020. Techno-economic feasibility and spatial analysis of thermochemical conversion pathways for regional poultry waste valorization. ACS Sustain. Chem. Eng. 8, 5763–5775.

Bulak, P., Proc-Pietrycha, K., Kaczor, M., Złotko, K., Polakowski, C., Wiącek, D., et al., 2023. A novel type of biochar from chitinous Hermetia illucens waste with a built-in stimulating effect on plants and soil arthropods. Sci. Rep. 13 (1), 8306.

Campuzano, R., González-Martínez, S., 2016. Characteristics of the organic fraction of municipal solid waste and methane production: a review. Waste Manag. 54, 3–12.

Canova, J.T., Nahar, S., Moss, T.W., 2025. From stigma to solution: sanitation and sustainable entrepreneurship in emerging economies. J. Bus. Ventur. Insights 23, e00532.

Caruso, D., Devic, E., Subamia, I.W., Talamond, P., Baras, E., 2014. Technical handbook of domestication and production of diptera black soldier fly (BSF) *Hermetia illucens*, stratiomyidae. Percetakan IPB, first ed.

Cheng, Z., Yu, L., Li, H., Xu, X., Yang, Z., 2021. Use of housefly (*Musca domestica* L.) larvae to bioconversion food waste for animal nutrition and organic fertilizer. Environ. Sci. Pollut. Control Ser. 28 (35), 48921–48928.

Cordell, D., Drangert, J.-O., White, S., 2009. The story of phosphorus: global food security and food for thought. Glob. Environ. Change 19, 292–305.

Cornelissen, G., Pandit, N.R., Taylor, P., Pandit, B.H., Sparrevik, M., Schmidt, H.P., 2016. Emissions and char quality of flame-curtain" Kon Tiki" Kilns for Farmer-Scale charcoal/biochar production. PLoS One 11 (5), e0154617.

Devault, M., Woolf, D., Lehmann, J., 2025. Nutrient recycling potential of excreta for global crop and grassland production. Nat. Sustain. 8, 99–111.

Devi, P., Eskicioglu, C., 2024. Effects of biochar on anaerobic digestion: a review. Environ. Chem. Lett. 1–42.

Dobermann, A., Bruulsema, T., Cakmak, I., Gerard, B., Majumdar, K., McLaughlin, M., et al., 2022. Responsible plant nutrition: a new paradigm to support food system transformation. Global Food Secur. 33, 100636.

Donley, N., Cox, C., Bennett, K., Temkin, A.M., Andrews, D.Q., Naidenko, O.V., 2024. Forever pesticides: a growing source of PFAS contamination in the environment. Environ. Health Perspect. 132 (7), 075003.

Doughty, K.H., Middleton, J.A., Salini, M.J., Kragt, M.E., Partridge, J.C., Hemmi, J.M., Martin, B.C., 2024. Food for thought: valuable bioproduction pathways emerge in a circular food production model. Cleaner Circ. Bioecon. 9, 100102.

Echevarria, D., Trimmer, J.T., Cusick, R.D., Guest, J.S., 2021. Defining nutrient colocation typologies for human-derived supply and crop demand to advance resource recovery. Environ. Sci. Technol. 55 (15), 10704–10713.

Ellen MacArthur Foundation, 2013. Circular economy principles. https://www.ellenmacarthurfoundation.org/. (Accessed 23 January 2025).

Elwert, C., Knips, I., Katz, H., 2010. A novel protein source: maggot meal of the black soldier fly (*Hermetia illucens*) in broiler feed. In: Gierus, M., Kluth, H., Bulang, M., Kluge, H. (Eds.), Tagung.

Espinosa-Marrón, A., Adams, K., Sinno, L., Cantu-Aldana, A., Tamez, M., Marrero, A., et al., 2022. Environmental impact of animal-based food production and the feasibility of a shift toward sustainable plant-based diets in the United States. Front. Sustain. 3, 841106.

Exton, Benjamin, Casas, Ana, Lewis, Amy, Willcock, Simon, Kupiec-Teahan, Beata, Barrington, Dani J., Anciano, Fiona, et al., 2025. Assessing the role of servicing in enhancing sanitation-related quality of life among container-based sanitation users. Nature Water 1–11.

Fabi, C., Cachia, F., Conforti, P., English, A., Moncayo, J.R., 2021. Improving data on food losses and waste: from theory to practice. Food Policy 98, 101934.

FAO, 2023–2024. FAOSTAT. Food and Agriculture Organization of the United Nations, Rome.

Farrell, M., Jones, D.L., 2009. Heavy metal contamination of a mixed waste compost: metal speciation and fate. Bioresour. Technol. 100 (19), 4423–4432.

Feng, Y., Rosa, L., 2024. Global biomethane and carbon dioxide removal potential through anaerobic digestion of waste biomass. Environ. Res. Lett. 19 (2), 024024.

Food and Agriculture Organization of the United Nations (FAO), 2021. Food loss and waste database. Rome. https://www.fao.org/platform-food-loss-waste/flw-data/en/.

Fu, B., Chen, L., Huang, H., Qu, P., Wei, Z., 2021. Impacts of crop residues on soil health: a review. Environ. Pollut. Bioavailab. 33 (1), 164–173.

Gao, X., Masiello, C., 2024. Biochar effects on water availability. In: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management. Rouledge, London, pp. 514–530.

George, V., 2024. Biochar Life is helping farmers double their income while saving the planet. Carbon Herald. Biochar Life Is Helping Farmers Double Their Income While Saving the Planet. (Accessed 19 December 2024).

Godfray, H. Charles J., Aveyard, Paul, Garnett, Tara, Hall, Jim W., Key, Timothy J., Lorimer, Jamie, Pierrehumbert, Ray T., Scarborough, Peter, Springmann, Marco, Jebb, Susan A., 2018. Meat consumption, health, and the environment. Science 361 (6399), eaam5324.

Growth Market Reports, 2024. Nutrient recovery from wastewater market research report 2033. https://growthmarketreports.com/report/nutrient-recovery-from-wastewater-market.

Gwara, S., Wale, E., Odindo, A., Buckley, C., 2021. Attitudes and perceptions on the agricultural use of human excreta and human excreta derived materials: a scoping review. Agriculture 11, 153, 2021.

Harder, R., Wielemaker, R., Larsen, T.A., Zeeman, G., Öberg, G., 2019. Recycling nutrients contained in human excreta to agriculture: pathways, processes, and products. Crit. Rev. Environ. Sci. Technol. 49 (8), 695–743.

Harder, R., Wielemaker, R., Molander, S., Öberg, G., 2020. Reframing human excreta management as part of food and farming systems. Water Res. 175, 115601.

Hoang, A.T., Goldfarb, J.L., Foley, A.M., Lichtfouse, E., Kumar, M., Xiao, L., et al., 2022. Production of biochar from crop residues and its application for anaerobic digestion. Bioresour. Technol. 363, 127970.

Huang, M., Zhu, Y., Li, Z., Huang, B., Luo, N., Liu, C., Zeng, G., 2016. Compost as a soil amendment to remediate heavy metal-contaminated agricultural soil: mechanisms, efficacy, problems, and strategies. Water, Air, Soil Pollut. 227, 1–18.

Joveniaux, A., Legrand, M., Esculier, F., De Gouvello, B., 2022. Towards the development of source separation and valorization of human excreta? Emerging dynamics and prospects in France. Front. Environ. Sci. 10, 976624.

Kaza, S., Yao, L., Bhada-Tata, P., Van Woerden, F., 2018. What a Waste 2.0: a Global Snapshot of Solid Waste Management to 2050. World Bank Publications.

Kerner, P., Struhs, E., Mirkouei, A., Aho, K., Lohse, K.A., Dungan, R.S., You, Y., 2023. Microbial responses to biochar soil amendment and influential factors: a three-level meta-analysis. Environ. Sci. Technol. 57 (48), 19838–19848.

Krahn, K.M., Cornelissen, G., Castro, G., Arp, H.P.H., Asimakopoulos, A.G., Wolf, R., et al., 2023. Sewage sludge biochars as effective PFAS-sorbents. J. Hazard Mater. 445, 130449.

Krounbi, L., Enders, A., Gaunt, J., Ball, M., Lehmann, J., 2021. Plant uptake of nitrogen adsorbed to biochars made from dairy manure. Sci. Rep. 11 (1), 15001.

Kästner, M., Miltner, A., 2016. Application of compost for effective bioremediation of organic contaminants and pollutants in soil. Appl. Microbiol. Biotechnol. 100, 3433–3449.

Kumar, V., Chopra, A.K., Kumar, A., 2017. A review on sewage sludge (Biosolids) a resource for sustainable agriculture. Archives Agri. Environ. Sci. 2 (4), 340–347.

Lair, A., Mansuy, M., Romand, C., Oberti, O., Pradels, C., Barina, G., Denoun, T., Venturini, M., Trommsdorff, C., 2024. Enhancing landfill efficiency to drive greenhouse gas reduction: a comprehensive study on best practices and policy recommendations. Waste Manag. Res. 42 (10), 889–900.

Larsen, T.A., Riechmann, M.E., Udert, K.M., 2021. State of the art of urine treatment technologies: a critical review. Water Res. X 13, 100114.

Lehmann, J., Barrios, E., Devault, M., Li, L., Nelson, R., Six, J., Trimmer, J., 2025. Biochar in the circular bionutrient economy. Proc. Natl. Acad. Sci. 122 (33), e2503668122.

Lehmann, J., Cowie, A., Masiello, C.A., Kammann, C., Woolf, D., Amonette, J.E., et al., 2021. Biochar in climate change mitigation. Nat. Geosci. 14 (12), 883–892.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – a review. Soil Biol. Biochem. 43 (9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022.

Lehmann, J., Joseph, S., 2024. Biochar for environmental management: an introduction. In: Biochar for Environmental Management. Routledge, pp. 1–14.

Li, P., Zhao, H., Cheng, C., Hou, T., Shen, D., Jiao, Y., 2024. A review on anaerobic co-digestion of sewage sludge with other organic wastes for methane production: mechanism, process, improvement and industrial application. Biomass Bioenergy 185, 107241.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J. O., Thies, J., Luizão, F.J., Petersen, J., Neves, E.G., 2006. Black carbon increases cation exchange capacity in soils. Soil Sci. Soc. Am. J. 70, 1719–1730.

Lohman, H.A., Trimmer, J.T., Katende, D., Mubasira, M., Nagirinya, M., Nsereko, F., et al., 2020. Advancing sustainable sanitation and agriculture through investments in human-derived nutrient systems. Environ. Sci. Technol. 54 (15), 9217–9227.

Lundy, M.E., Parrella, M.P., 2015. Crickets are not a free lunch: protein capture from scalable organic side-streams via high-density populations of Acheta domesticus. PLoS One 10 (4), e0118785.

Marchuk, S., Tait, S., Sinha, P., Harris, P., Antille, D.L., McCabe, B.K., 2023. Biosolids-derived fertilisers: a review of challenges and opportunities. Sci. Total Environ. 875, 162555.

Marconi, P., Rosa, L., 2024. Global potential nitrogen recovery from anaerobic digestion of agricultural residues. Environ. Res. Lett. 19 (5), 054050.

Martin, T.M., Esculier, F., Levavasseur, F., Houot, S., 2022. Human urine-based fertilizers: a review. Crit. Rev. Environ. Sci. Technol. 52 (6), 890–936.

Maurer, M., Pronk, W., Larsen, T.A., 2006. Treatment processes for source-separated urine. Water Res. 40 (17), 3151–3166. https://doi.org/10.1016/j.watres.2006.07.012.

McKenna, P., Zakaria, F., Guest, J., Evans, B., Banwart, S., 2023. Will the circle be unbroken? The climate mitigation and sustainable development given by a circular economy of carbon, nitrogen, phosphorus and water. RSC Sustain. 1 (4), 960–974.

Menegat, S., Ledo, A., Tirado, R., 2022. Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture. Nat. Scientific Rep. 12 (1), 1–13.

Moebius-Clune, B.N., Van Es, H.M., Idowu, O.J., Schindelbeck, R.R., Moebius-Clune, D. J., Wolfe, D.W., Abawi, G.S., Thies, J.E., Gugino, B.K., Lucey, R., 2008. Long-Term effects of harvesting maize stover and tillage on soil quality. Soil Sci. Soc. Am. J. 72 (4), 960–969. https://doi.org/10.2136/sssaj2007.0248.

Moraes, N.V., Lermen, F.H., Echeveste, M.E.S., 2021. A systematic literature review on food waste/loss prevention and minimization methods. J. Environ. Manag. 286, 112268.

Morais, M.A.C., Ishida, A., 2025. An overview of residential food waste recycling initiatives in Japan. Clean. Waste Syst., 100232

Moruzzo, R., Riccioli, F., Espinosa Diaz, S., Secci, C., Poli, G., Mancini, S., 2021. Mealworm (*Tenebrio molitor*): potential and challenges to promote circular economy. Animals 11 (9), 2568.

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., Gerber, P., 2017. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. Global Food Secur. 14, 1–8.

Mouratiadou, I., Stella, T., Gaiser, T., Wicke, B., Nendel, C., Ewert, F., van der Hilst, F., 2020. Sustainable intensification of crop residue exploitation for bioenergy: opportunities and challenges. GCB Bioenergy 12 (1), 71–89.

Muola, A., Fuchs, B., Laihonen, M., Rainio, K., Heikkonen, L., Ruuskanen, S., Saikkonen, K., Helander, M., 2021. Risk in the circular food economy: Glyphosate-based herbicide residues in manure fertilizers decrease crop yield. Sci. Total Environ. 750, 141422. https://doi.org/10.1016/j.scitotenv.2020.141422.

NASEM (US National Academies of Sciences, Engineering, and Medicine), 2024. Exploring Linkages Between Soil Health and Human Health. The National Academies Press, Washington, DC. https://doi.org/10.17226/27459.

Nedelciu, C.E., Ragnarsdottir, K.V., Schlyter, P., Stjernquist, I., 2020. Global phosphorus supply chain dynamics: assessing regional impact to 2050. Global Food Secur. 26, 100426.

Netherway, P., Reichman, S.M., Laidlaw, M., Scheckel, K., Pingitore, N., Gascó, G., et al., 2019. Phosphorus-rich biochars can transform lead in an urban contaminated soil. J. Environ. Qual. 48 (4), 1091–1099.

Ngure, F.M., Reid, B.M., Humphrey, J.H., Mbuya, M.N., Pelto, G., Stoltzfus, R.J., 2014. Water, sanitation, and hygiene (WASH), environmental enteropathy, nutrition, and early child development: making the links. Ann. N. Y. Acad. Sci. 1308 (1), 118–128.

Nguyen, M.K., Lin, C., Hoang, H.G., Sanderson, P., Dang, B.T., Bui, X.T., et al., 2022. Evaluate the role of biochar during the organic waste composting process: a critical review. Chemosphere 299, 134488.

Nkomo, N., Odindo, A.O., Musazura, W., Missengue, R., 2021. Optimising pyrolysis conditions for high-quality biochar production using black soldier fly larvae faecal-derived residue as feedstock. Heliyon 7 (5), e07025.

Papargyropoulou, E., Lozano, R., Steinberger, J.K., Wright, N., bin Ujang, Z., 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. J. Clean. Prod. 76, 106–115.

Paudel, P.P., Kafle, S., Park, S., Kim, S.J., Cho, L., Kim, D.H., 2024. Advancements in sustainable thermochemical conversion of agricultural crop residues: a systematic review of technical progress, applications, perspectives, and challenges. Renew. Sustain. Energy Rev. 202, 114723.

Pender, A., Kelleher, L., O'Neill, E., 2024. Regulation of the bioeconomy: barriers, drivers and potential for innovation in the case of Ireland. Cleaner Circ. Bioecon. 7, 100070.

Pickering, S.D., Gökçe, Ö., Hanna, D., Knell, M., Lee, D., Scales, M., et al., 2024. Public perceptions of human excretion-based fertiliser in England and Japan. Waste Manag. Bull. 2 (4), 11–20.

Popoola, L.T., Olawale, T.O., Salami, L., 2023. A review on the fate and effects of contaminants in biosolids applied on land: hazards and government regulatory policies. Heliyon, e19788.

Pozzebon, E.A., Seifert, L., 2023. Emerging environmental health risks associated with the land application of biosolids: a scoping review. Environ. Health 22 (1), 57.

Raman, S.S., Stringer, L.C., Bruce, N.C., Chong, C.S., 2022. Opportunities, challenges and solutions for black soldier fly larvae-based animal feed production. J. Clean. Prod. 373, 133802. https://doi.org/10.1016/j.jclepro.2022.133802.

Robinson, T.P., Wint, G.W., Conchedda, G., Van Boeckel, T.P., Ercoli, V., Palamara, E., et al., 2014. Mapping the global distribution of livestock. PLoS One 9 (5), e96084.

Rosemarin, A., Macura, B., Carolus, J., Barquet, K., Ek, F., Järnberg, L., Lorick, D., Johannesdottir, S., Pedersen, S.M., Koskiaho, J., Haddaway, N.R., Okruszko, T., 2020. Circular nutrient solutions for agriculture and wastewater – a review of technologies and practices. Curr. Opin. Environ. Sustain. 45, 78–91. https://doi.org/10.1016/j.cosust.2020.09.007.

Russel, K.C., Hughes, K., Roach, M., Auerbach, D., Foote, A., Kramer, S., Briceño, R., 2019. Taking container-based sanitation to scale: opportunities and challenges. Front. Environ. Sci. 7, 190.

Ryen, E.G., Babbitt, C.W., 2022. The role of US policy in advancing circular economy solutions for wasted food. J. Clean. Prod. 369, 133200.

Saliu, T.D., Oladoja, N.A., Sauvé, S., 2024. Eco-friendly and sustainability assessment of technologies for nutrient recovery from human urine—a review. Front. Sustain. 4, 1338380.

Saqib, Z., Sadef, Y., 2025. Sustainable waste management through commercial composting: challenges, opportunities, and future directions for circular economy. Eur. J. Sustain. Dev. Res. 9 (4). https://doi.org/10.29333/ejosdr/16579 em0319.

Scarlat, N., Martinov, M., Dallemand, J.F., 2010. Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use. Waste Manag. 30 (10), 1889–1897.

Schmidt, H.P., Pandit, B.H., Cornelissen, G., Kammann, C.I., 2017. Biochar-based fertilization with liquid nutrient enrichment: 21 field trials covering 13 crop species in Nepal. Land Degrad. Dev. 28 (8), 2324–2342.

Söderholm, K., Vidal, B., Hedström, A., Herrmann, I., 2023. Flexible and resource-recovery sanitation solutions: what hindered their implementation? A 40-year Swedish perspective. J. Urban Technol. 30 (1), 23–45.

Simha, P., Karlsson, C., Viskari, E.L., Malila, R., Vinnerås, B., 2020. Field testing a pilot-scale system for alkaline dehydration of source-separated human urine: a case study in Finland. Front. Environ. Sci. 8, 570637.

Simons, A.M., Ahmed, M., Blalock, G., Nesin, B., 2023. Indigenous bone fertilizer for growth and food security: a local solution to a global challenge. Food Policy 114, 102396.

Smerald, A., Rahimi, J., Scheer, C., 2023. A global dataset for the production and usage of cereal residues in the period 1997–2021. Sci. Data 10 (1), 685.

Smith, W.N., Grant, B.B., Campbell, C.A., McConkey, B.G., Desjardins, R.L., Kröbel, R., Malhi, S.S., 2012. Crop residue removal effects on soil carbon: measured and inter-model comparisons. Agric. Ecosyst. Environ. 161, 27–38.

Snyder, W.S., Cook, M.J., Tipton, I.H., Nasset, E.S., Karhausen, L.R., Howells, G.P., 1975. Reference Man: Anatomical, Physiological and Metabolic Characteristics, Ser. Report of Task Group on Reference Man-International Commission on Radiological Protection.

Solidaridad Network, 2023. Carbon credits and carbon markets: unlocking benefits for smallholder farmers. Carbon Credits and Carbon Markets: Unlocking Benefits for Smallholder Farmers - Solidaridad Network. (Accessed 10 December 2024).

Spiegal, S., Kleinman, P.J., Endale, D.M., Bryant, R.B., Dell, C., Goslee, S., et al., 2020. Manuresheds: advancing nutrient recycling in US agriculture. Agric. Syst. 182, 102813.

Sørmo, E., Krahn, K.M., Flatabø, G.Ø., Hartnik, T., Arp, H.P.H., Cornelissen, G., 2024. Distribution of PAHs, PCBs, and PCDD/Fs in products from full-scale relevant pyrolysis of diverse contaminated organic waste. J. Hazard Mater. 461, 132546.

Tan, J.K.N., Lee, J.T.E., Chiam, Z., Song, S., Arora, S., Tong, Y.W., Tan, H.T.W., 2021. Applications of food waste-derived black soldier fly larval frass as incorporated compost, side-dress fertilizer and frass-tea drench for soilless cultivation of leafy vegetables in biochar-based growing media. Waste Manag. 130, 155–166.

Tao, Y., Liu, Z., Zheng, J., Zhou, J., He, D., Ma, J., 2022. Microalgae production in human urine: fundamentals, opportunities, and perspectives. Front. Microbiol. 13, 1067782.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418 (6898), 671–677.

Timshina, A.S., Robey, N.M., Oldnettle, A., Barron, S., Mehdi, Q., Cerlanek, A., et al., 2024. Investigating the sources and fate of per-and polyfluoroalkyl substances (PFAS) in food waste compost. Waste Manag. 180, 125–134.

Trimmer, J.T., Cusick, R.D., Guest, J.S., 2017. Amplifying progress toward multiple development goals through resource recovery from sanitation. Environ. Sci. Technol. 51 (18), 10765–10776.

Trimmer, J.T., Guest, J.S., 2018. Recirculation of human-derived nutrients from cities to agriculture across six continents. Nat. Sustain. 1 (8), 427–435.

UNEP (United Nations Environment Programme), 2021. Promoting sustainable practices and innovative solutions for curbing food loss and waste. https://open.unep.org/resolution/outcome-report/257.

UNEP, 2024a. Global Waste Management Outlook 2024. UNEP, Nairobi.

UNEPb, 2024b. Food waste index report 2024. Think eat save: tracking progress to halve global food waste. https://wedocs.unep.org/20.500.11822/45230.

Van Asselt, E.D., Arrizabalaga-Larrañaga, A., Focker, M., Berendsen, B.J.A., Van de Schans, M.G.M., Van der Fels-Klerx, H.J., 2023. Chemical food safety hazards in circular food systems: a review. Crit. Rev. Food Sci. Nutr. 63 (30), 10319–10331.

van den Broek, S., Nybom, I., Hartmann, M., Doetterl, S., Garland, G., 2024. Opportunities and challenges of using human excreta-derived fertilizers in agriculture: a review of suitability, environmental impact and societal acceptance. Sci. Total Environ. 957, 177306.

van der Fels-Klerx, H.J., van Asselt, E.D., Berendsen, B., Focker, M.F., 2024. Framework for evaluation of food safety in the circular food system. Sci. Food 8 (1), 36.

van Huis, A., 2015. Edible insects contributing to food security? Agric. Food Secur. 4, 20. https://doi.org/10.1186/s40066-015-0041-5.

Van Zanten, H.H., Van Ittersum, M.K., De Boer, I.J., 2019. The role of farm animals in a circular food system. Global Food Secur. 21, 18–22.

Vilela, S.J., Andronicos, N.M., Kolakshyapati, M., Hilliar, M., Sibanda, T.Z., Andrew, N. R., Swick, R.A., Wilkinson, S., Ruhnke, I., 2021. Black soldier fly larvae in broiler diets improve broiler performance and modulate the immune system. Anim. Nutr. 7 (3), 695–706. https://doi.org/10.1016/j.aninu.2020.08.014.

Wang, Y., Fang, M., Lou, Z., He, H., Guo, Y., Pi, X., Wang, Y., Ke, Y., Fei, X., 2024. Methane emissions from landfills differentially underestimated worldwide. Nat. Sustain. 7, 496–507. https://doi.org/10.1038/s41893-024-01307-9.

Werner, K.A., Castro-Herrera, D., Yimer, F., Tadesse, M., Kim, D.G., Prost, K., et al., 2023. Microbial risk assessment of mature compost from human excreta, cattle manure, organic waste, and biochar. Sustainability 15 (5), 4624.

Werther, J., Ogada, T., 1999. Sewage sludge combustion. Prog. Energy Combust. Sci. 25 (1), 55–116.

WHO/UNICEF, 2017. Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines. UNICEF and World Health Organization Joint Monitoring Programme.

Woolf, D., Lehmann, J., Ogle, S., Kishimoto-Mo, A.W., McConkey, B., Baldock, J., 2021. Greenhouse gas inventory model for biochar additions to soil. Environ. Sci. Technol. 55 (21), 14795–14805.

World Bank Group, 2019. Evaluating the Potential of Container-Based Sanitation. World Bank.

Wu, S., He, H., Inthapanya, X., Yang, C., Lu, L., Zeng, G., Han, Z., 2017. Role of biochar on composting of organic wastes and remediation of contaminated soils—a review. Environ. Sci. Pollut. Control Ser. 24, 16560–16577.

Xu, X., Sharma, P., Shu, S., Lin, T.S., Ciais, P., Tubiello, F.N., et al., 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nat. Food 2 (9), 724–732.

Yang, X., Lan, Y., Meng, J., Chen, W., Huang, Y., Cheng, X., et al., 2017. Effects of maize stover and its derived biochar on greenhouse gases emissions and C-budget of brown earth in Northeast China. Environ. Sci. Pollut. Control Ser. 24, 8200–8209.

Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B., Sabir, M., 2020. Biochar effects on crop yields with and without fertilizer: a meta-analysis of field studies using separate controls. Soil Use Manag. 36, 2–18.

Yin, Y., Yang, C., Li, M., Zheng, Y., Ge, C., Gu, J., et al., 2021. Research progress and prospects for using biochar to mitigate greenhouse gas emissions during composting: a review. Sci. Total Environ. 798, 149294.

Yuan, P., Wang, J., Pan, Y., Shen, B., Wu, C., 2019. Review of biochar for the management of contaminated soil: preparation, application and prospect. Sci. Total Environ. 659, 473–490.

Zhao, N., Lehmann, J., You, F., 2020. Poultry waste valorization via pyrolysis technologies: economic and environmental life cycle optimization for sustainable bioenergy systems. ACS Sustain. Chem. Eng. 8 (11), 4633–4646.

Zhao, W., Hu, T., Ma, H., Li, D., Zhao, Q., Jiang, J., Wei, L., 2024. A review of microbial responses to biochar addition in anaerobic digestion system: community, cellular and genetic level findings. Bioresour. Technol. 391, 129929.