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TOPICAL REVIEW

Potential for improving nutrient use efficiencies of human food systems with a circular economy of organic wastes and fertilizer

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Abstract

Waste from the human food system includes a large quantity of nutrients that pose environmental and human health risks. If these nutrients can be captured and repurposed, they could potentially offset synthetic fertilizer demands. This study reviews several technologies—including anaerobic digestion, hydrothermal carbonization (HTC), and composting—that can be used to process wastes from the human food system. This study also assesses the quantity of nutrient resources that are available from wastes, including food waste, biosolids, manure, and yard waste. Three geographic scales were analyzed. At a national level in the United States, up to 27% of nitrogen and 33% of phosphorus demands for agriculture could be met with wastes from the human food system, primarily from food waste and biosolids. Some rural localities have a greater potential for circular economies of nutrients in the food system, with the potential to meet 100% of nitrogen and phosphorus fertilizer demands using waste nutrients, as in the case of Athens County, Ohio. Benefits of offsetting synthetic fertilizer use with waste nutrients include reduced greenhouse gas (GHG) emissions, with up to 64% reduction in GHG emissions per unit of nitrogen fertilizer produced with HTC.

1. Introduction

Wastes from human food systems include agricultural waste, pre-consumer food waste, and post-consumer food waste in addition to biosolids that are usually treated with wastewater. Management of these wastes often occurs separately under the respective supervision of farm managers, food service agencies, food processors, and wastewater treatment plants (WWTPs); but there is a need for reducing waste in all cases. If valuable products can be made from wastes, circular economies become possible (Davis *et al* 2016). Although the composition of organic wastes varies across sectors, all have nutrients in common that could be used to generate fertilizer. This review evaluates the aggregate waste associated with the human food system to identify how new technologies and circular economies might improve biological nutrient use efficiency.

Nutrient use efficiency is a concept rigorously addressed in the ecological sciences (e.g. Vitousek 1982, Meena and Meena 2017) and has been extended to agricultural ecosystems (e.g. Baligar *et al* 2001, Zhang *et al* 2010, Singh *et al* 2021). Food wastes and biosolids have been treated more comprehensively in the engineering sciences (e.g. Metcalf *et al* 1991, Thassitou and Arvanitoyannis 2001, Tchobanoglous *et al* 2003, Ma and Liu 2019), with emphasis on reducing health risk associated with waste. Recent advances in technological applications for processing organic waste present a new opportunity for valuing nutrients. To advance our understanding of this opportunity, a holistic assessment of multiple waste streams that stem from human food systems is needed.

The mass of wastes from food systems is substantial. Agricultural wastes include manure from livestock and crop residues, which equaled an aggregate annual amount of 34.2 million dry tons in the US in 2016 (Langholtz *et al* 2016). Between 30% and 40% of the food supply in the US food system is wasted, a total of >63 million tons in 2018 (EPA 2023), 56% of which was landfilled. The amount of food wastes generated in the US has increased along with total municipal solid wastes, which was 3.3 times greater in 2018 than it was in 1960 (EPA 2022). Biosolids represent the largest portion of organic wastes, and these are usually treated at WWTPs.

An estimated 18% of US residents are not connected to municipal sewer systems with wastewater treatment (EPA 2021), but biosolids from home sewage treatment systems (HSTS) are currently poorly characterized in the US. Most of the populations in the US that rely on some form of HSTS, like septic tanks, are located in rural regions (EPA 2021). Many of these rural regions, such as southeastern Ohio, have a high percentage of poorly maintained or ineffective HSTS that contribute to nutrient loading in local watersheds (OEPA 2018). Septic systems are more common in southeastern Ohio than in other parts of the state and country, with an estimated 8000–9000 home septic systems in Athens County alone (Saha *et al* 2021).

Despite the substantial capital invested in waste management, there is an unrealized potential for capturing valuable nutrients from waste streams. There is a large and growing market for nutrients in fertilizers, for instance, that could be supplemented with waste nutrients. Farmers in the US manufacture and consume synthetic fertilizers at a pace of 23.4 million tons annually (USDA 2017), and annual revenue from the fertilizer industry is ∼$20 billion (Ristoff 2022). If wastes can be captured and repurposed for fertilizer, a circular economy for nutrients in the human food system can develop.

Several recent technological developments present opportunities for processing waste into alternative products. Hydrothermal carbonization (HTC) is one process that can yield nutrient-rich products that substitute as fertilizer (Adjuik *et al* 2020, Saha *et al* 2021). In HTC, high temperatures (180 °C–220 °C) are used to treat waste mixtures (e.g. McGaughy and Reza 2018), yielding a pathogen-free and upgraded product useful as fertilizer (Adjuik *et al* 2020). The energy input required for HTC is lower than energy inputs typical in pyrolysis, and HTC is more easily performed on feedstocks with high water content than pyrolysis. Products of HTC are sometimes used as a fuel source (an alternative to coal, for instance), but feedstocks with lower proportions of carbon and higher concentrations of nitrogen and phosphorus are suited to fertilizer applications.

Other technologies for processing organic wastes include anaerobic digestion (AD) and composting. Anaerobic digestion, a process that involves biochemical decomposition of organic material in anoxic conditions to produce biogas and a nutrient rich digestate, has a growing number of applications in the US (USDA 2014, EPA 2020). Mixed wastes can be processed using AD (e.g. David *et al* 2018, Herman *et al* 2022) and there are AD plants operating at a range of volumes, from small-scale farm systems (e.g. Miller *et al* 2021) to large-scale industrial systems (e.g. Delgenes *et al* 2002). The digestate from AD can be used as a fertilizer in agriculture (e.g. Alburquerque *et al* 2012, Adjuik *et al* 2020). In contrast with AD, composting is a process that involves aerobic decomposition of organic wastes and is usually accomplished with a mixture of wet, high nutrient wastes, and dry wastes that have a greater proportion of carbon. Food waste, agricultural residues, yard wastes, and manures are often mixed in composting, but biosolids from human waste are not typically composted. All of these organic wastes, including biosolids, are processed in AD systems.

The purpose of this analysis is to determine the quantity and value of nutrients that can be produced from human wastes, including biosolids, food waste, manure, and garden yard wastes that are all products of the food system. Quantities of waste were estimated for three geographic scales: US national-level, state-level for the state of Ohio, and county level in Athens, OH, a rural Appalachian county known to have many HSTS (Saha *et al* 2021). Three processing technologies (AD, HTC, and composting) were evaluated for processing wastes. For each geographic scale, the potential nutrient production from wastes was compared to nutrient consumption for fertilizer in the region to test the hypothesis that nutrient balances can be met by deploying a circular economy in agriculture-food-waste systems.

2. Methods

Estimates of the mass of waste generated from the food system in the United States and the state of Ohio were calculated using publicly available datasets from the Environmental Protection Agency (EPA 2011, 2017, 2022). The nutrient composition of different waste types was estimated from means of previously published measurements. A literature review was conducted in July of 2021 and again during a period from July of 2022 through January of 2023 to identify previously published measurements of nitrogen and phosphorus concentrations in different wastes. Keywords searched in GoogleScholar and the ArticlesPlus database (which includes > 200 databases like EBSCO and JSTOR) included nitrogen or phosphorus or nutrient values or NPK combined with manure or agricultural residues or yard waste or green waste or food waste or human waste or biosolids or septage or sewage or feces or urine (see supplementary material).

All published studies that addressed nutrient values in food waste and biosolids were filtered

Table 1. Fertilizer amounts consumed for agriculture in the United States summarized by nutrient, with market value and change in value between 2015 and 2022.

	US consumption[a] of fertilizer (Mg)	Value (2022 prices)	Value (2014/2015 prices)	% change in value
Nitrogen	11 347 070	$ 18 717 404 995	$ 13 138 827 770	42%
Phosphorus	1718 170	$ 5322 903 689	$ 4372 451 206	22%

[a] *consumption based on 2018–19 US consumption reported by IFASTAT (2023), details included in supplemental material.*

to include values reported for populations living in developed economies that reflect the average American diet. After reviewing all remaining studies for relevant numbers, 21 total studies were used to estimate nutrient values: five for biosolids (Del Porto and Steinfeld 1999, Werner *et al* 2000, Johansson *et al* 2001, Evans 2015, Rose *et al* 2015), eight for food waste (Zhang *et al* 2007, Bernstad and la Cour Jansen 2011, Evangelisti *et al* 2014, Fung *et al* 2019, Pagliaccia *et al* 2019, Haouas *et al* 2021, AHRC 2022, Herman *et al* 2022), three for manure (Abd El Lateef *et al* 2021, Allotment Garden 2022, Prado *et al* 2022), and five for yard waste (Holtz and Caesar-TonThat 2004, Tahboub *et al* 2007, EPA 2017, Holtz and Culumber 2019, TNC 2022). The mean nutrient content and total mass of waste in each category were used to estimate the total amount of nutrients available from wastes (see supplemental material).

Fertilizer demand and market value (table 1) were determined using databases maintained by the International Fertilizer Association (IFASTAT 2023), the USDA Agricultural Census and USDA Agricultural Marketing Service. Estimates of the amounts of fertilizer consumed in the United States, in Ohio, and in a rural county (Athens) of Ohio (USDA ERS 2019, IFASTAT 2023) were used to define quantities appropriate for a business-as-usual (BAU) reference estimate of fertilizer market values (Quinn 2022, Schnitkey *et al* 2022, TNC 2022, Intratec 2023, Trading Economics 2023, Triple Superphosphate Spot Price 2023, US Urea Spot Price 2023), and greenhouse gas (GHG) emissions from fertilizer manufacturing (Wood and Cowie 2004, Albaugh *et al* 2012, Brentrup *et al* 2016, Hoxha and Christensen 2019, Walling and Vaneeckhaute 2020). The potential for offsetting fertilizer nutrients with different waste sources was quantified and three technologies for processing wastes were assessed to determine the nutrient yield and GHG intensity of these alternative pathways for waste.

Scenarios for sourcing nutrients from different waste streams using alternate technologies (compost, AD, HTC) were compared to the BAU case. The nutrient yield after processing waste in each technology and the GHG emissions of each technology were assessed using previously published literature. Varied combinations of wastes were evaluated for each processing technology, including an assessment of the nutrient yields for fertilizer. Scenarios were compared to assess differences in the amount of nutrients that could be recovered for fertilizer, the climate mitigation potential (i.e. GHG emissions reduction) associated with displacing fertilizers used in the BAU, and the proportion of the total nutrient demand that could be met by waste nutrients. The following categories of organic wastes were evaluated:

1. Food waste
2. Biosolids
3. Manure
4. Yard waste
5. Manure and yard waste
6. Food waste and manure
7. Food waste, manure, and biosolids
8. Biosolids, manure, and yard waste
9. Food waste, biosolids, manure, yard waste

To evaluate the potential for a circular economy, production of nutrients from wastes in each scenario (waste category x processing technology) was compared with the fertilizer demand at three geographic scales to characterize the potential to meet fertilizer demands.

The proportion of biosolid waste associated with HSTS in Ohio and Athens County was estimated to further assess the potential for offsetting fertilizer demands with this localized source of biosolids that currently poses a liability for homeowners due to environmental and human health risks. Spatial boundaries for analysis of biosolids constrained to HSTS within Athens County were determined at the township/city level, which are the smallest geographical areas within the county for which population and wastewater information were available. Locations of WWTPs and their service areas were verified using Ohio EPA permits and with direct conversations with local water/sewer department managers. All waste and nutrient estimates within a given geospatial boundary were estimated per capita using the 2020 United States Census data, the American Community Survey for each designated city/township, and with geographical boundaries defined by the Transportation Information Mapping System from the Ohio Department of Transportation. Except for Athens Township, all townships were assumed to use HSTS in the unincorporated fraction of the township (figure 1). The Plains in Athens township (an unincorporated Census Designated Place) has a

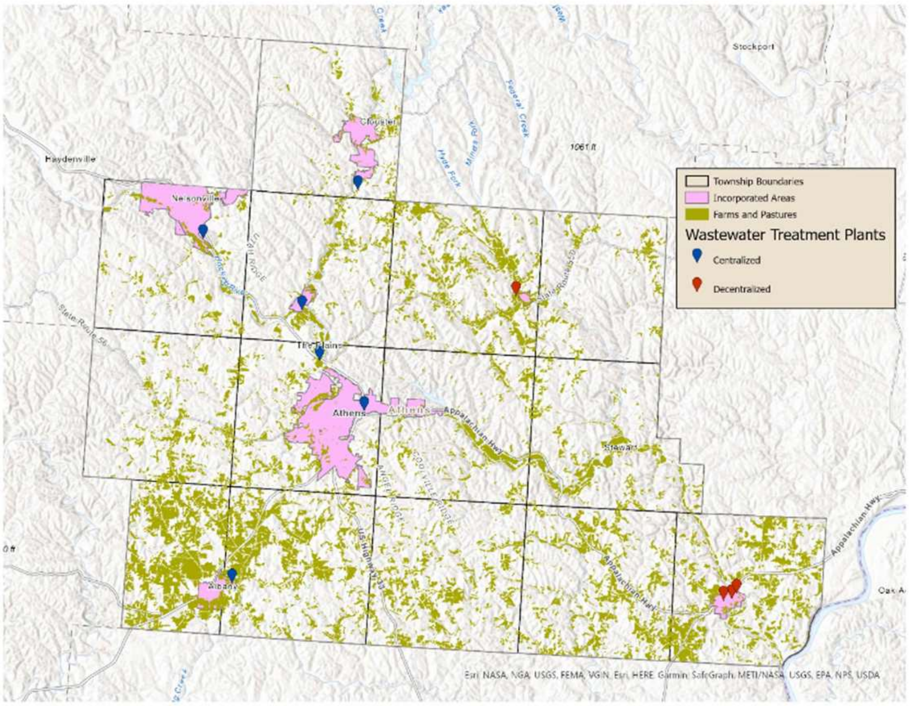

Figure 1. Map of region for analysis with sewer lines spatially resolved in the incorporated regions (pink) and HSTS in all locations outside of the incorporated regions. Locations of WWTPs are marked in blue (centralized) and red (decentralized) and the farms and pastures that have fertilizer demand are designated in green.

wastewater treatment system in place, and thus the population of The Plains was removed from Athens township when calculating waste in HSTS. Nutrient heatmaps for human waste were generated by multiplying the nutrient mass in human waste per capita per day by the population in each township that relies on HSTS.

3. Results

In total, over 3.38 million metric tons of nitrogen and nearly 574 thousand metric tons of phosphorus are embodied in organic wastes produced in the US annually (table 2). Food waste represents a larger mass of nutrients than the biosolids, manure, or yard waste produced in the US (table 2). Food waste alone contains more phosphorus than biosolids, manure, and yard waste combined.

The three technologies examined for treating organic wastes indicate 28%–33% of the phosphorus fertilizer demand and 11%–27% of the nitrogen fertilizer demand in the US could be met with organic wastes (table 3). Anaerobic digestion has the greatest nutrient yield of the processing technologies, with 89% of nitrogen and 95% of phosphorus retained throughout the treatment process. HTC, however, is the processing technology with the lowest GHG emissions during processing (table 3).

Food waste increased substantially between 2010 and 2018, and with this increase, there are greater nutrients available for fertilizer applications in both Ohio and Athens County, and a greater potential to reduce the GHG emissions associated with fertilizer manufacturing (table 4).

Fertilizer consumption in the US exceeds 11.3 million metric tons (BAU scenario), and fertilizer manufacturing technologies, using wastes as feedstock, would offset the GHG emissions associated with manufacturing this fertilizer (table 5). Of the three technologies reviewed, HTC has the lowest GHG emissions, which were 64% lower than the BAU reference. Composting, however, results in greater net GHG emission than BAU with synthetic fertilizers.

The amount of nutrients embodied in organic wastes produced in Ohio could meet 50% of the nitrogen demand and 36% of phosphorus demand in the agricultural sector of the state (table 6). Nutrients from organic wastes produced in Athens County exceed the agricultural demand for nutrients in the county by more than four-fold (table 6). With 40% of the population in Athens county relying on HSTS (figure 2), the amount of nutrients available from HSTS alone is 1.7 times greater than the amount of nitrogen consumed in fertilizer in the county. The proportion of waste nutrients processed in HSTS is greater, by more than double, in Athens County than the national average in the US (figure 2). The

Table 2. Total nitrogen and phosphorus in wastes produced in the United States annually.[a]

Waste Type	Nitrogen content (Mg y^{-1})	Phosphorus content (Mg y^{-1})
Food Waste	1624 654	298 392
Biosolids	1512 238	181 468
Manure	83 569	46 665
Yard Waste	163 998	47 454
Manure + Yard Waste	247 566	94 118
Food Waste + Manure	1708 223	345 057
Food Waste + Manure + Biosolids	3220 461	526 525
Biosolids + Manure + Yard Waste	1759 804	275 586
Biosolids + Manure + Yard Waste + Food Waste	3384 458	573 979

[a] Sources: Abd El Lateef *et al* (2021), AHRC (2022), Bernstad and la Cour Jansen (2011), Allotment Garden (2022), TNC (2022).; Urine 24-Hour Volume Test: Purpose, Procedure, and Results (2012), U.S. Census Bureau QuickFacts: Ohio (2023), Fung *et al* (2019), Haouas *et al* (2021), Holtz and Culumber (2019), Johansson *et al* (2001), Langholtz *et al* (2016), Holtz and Caesar-TonThat (2004), Pagliaccia *et al* (2019), Prado *et al* (2022), Rose *et al* (2015), Del Porto and Steinfeld (1999), Tahboub *et al* (2007), EPA (2017), (EPA 2022), Zhang *et al* (2007).

concentration of nutrients available from biosolids more generally is related to population density and there is a large amount available in more populous cities and townships (figure 3).

4. Discussion

This analysis of wastes from human systems indicates that food waste, yard waste, and biosolids produced after human consumption of food can be a substantial source of nutrients to offset fertilizer demands in the US. In some rural locations, like Athens County in southeastern Ohio, the amount of nutrients in organic wastes exceeds the nutrient demand in agriculture, suggesting a circular economy of nutrients in the food system is feasible. At larger geographic scales, the amount of nutrients available from wastes is less than the agricultural demand for fertilizer, but there is still potential to offset a large fraction of fertilizer demands; nearly half of the nutrient fertilizer demand in the state of Ohio could be met with waste nutrients and nearly a third of US fertilizer demand could be met with waste nutrients. The exact amount of fertilizer that can be made from waste nutrient resources depends on processing technologies, with AD retaining the greatest amount the waste nutrients (89%–95%) during processing. Benefits of recycling waste nutrients back to agricultural systems include a reduction in GHG emissions relative to BAU fertilizer manufacturing, with the greatest reduction achieved if wastes are processed using HTC.

The spatial boundary applied to waste nutrients affects the scale of opportunity associated with both the financial and environmental benefits of processing human organic waste streams for fertilizer. A rural county like Athens has the opportunity to capture wastes from nutrients, offset 100% of the local fertilizer demand with this resource, and export the additional nutrient fertilizers to external markets. Because this county also has a large number of HSTSs, many of which are poorly maintained (Saha *et al* 2021), there is a substantial environmental benefit associated with implementing technology that would upgrade wastes to fertilizer products. The ability to export nutrients to external markets is only possible because the farms in the county are mostly small-scale operations. Counties that have more commercial-scale farms and well-maintained sewer systems would have lower potential to export nutrient products, but would still benefit from offsetting synthetic fertilizers with organic waste sources because of the lower GHG emissions associated with processing technologies like HTC.

When a larger spatial scale is applied, the percentage of total nutrient demand that can be offset with organic wastes declines, but up to 27% of nitrogen and 33% of phosphorus fertilizer demand in the US could be offset with nutrients from wastes (table 3). The largest sources of waste nutrients associated with the food system are food waste and biosolids. While reduction of food waste would help to achieve some sustainability goals, and both the US EPA (2022) and USDA (Buzby *et al* 2014) have prioritized a focus on food waste reduction, the percentage of food wasted continues to increase. Between 2010 and 2018, the amount of food wasted in the US increased by 76% (EPA 2011, 2022). The majority (60%) of this food waste in 2019 ended up in landfills (EPA 2023). An increasing amount of food waste is composted, but this represented only 5% of the total food waste in 2019 (EPA 2023). Also, according to our analysis, composting results in greater GHG emissions than other processing technologies.

Applications of both AD and HTC are increasing in capacity, but neither of these technologies are widely used in US to offset fertilizer use. These technologies require new infrastructure and skilled labor to operate, and therefore greater investment

Table 3. Yield of nitrogen (N) and phosphorus (P) and GHG emission ($CO_{2\,eq}$) by technology and category of organic waste.

Technology	Waste Type	% yield N after treatment[a]	% yield of P after treatment[b]	kg CO_2 eq emissions/ kg N[c]	kg CO_2 eq emissions/ kg P[d]	Potential offset of US N demand[e]	Potential offset of US P demand[f]
Compost	Food Waste	53%	100%	17.0	92.4	8%	17%
	Biosolids (Urine)	53%	100%	51.7	593.9	6%	7%
	Biosolids (Feces)	53%	100%	44.4	132.0	1%	4%
	Manure	53%	100%	63.4	113.1	0%	3%
	Yard Waste	53%	100%	95.0	316.8	1%	3%
	Manure + Yard Waste	53%	100%			1%	5%
	Food Waste + Manure	53%	100%			8%	20%
	Food Waste + Manure + Biosolids	53%	100%			15%	31%
	Biosolids + Manure + Yard Waste	53%	100%			8%	16%
	Biosolids + Manure + Yard Waste + Food Waste	53%	100%			16%	33%
Anaerobic Digestion	Food Waste	89%	95%	1.7	9.1	13%	17%
	Biosolids (Urine)	89%	95%	5.1	58.2	10%	7%
	Biosolids (Feces)	89%	95%	4.4	12.9	1%	4%
	Manure	89%	95%	6.2	11.1	1%	3%
	Yard Waste	89%	95%	9.3	31.0	1%	3%
	Manure + Yard Waste	89%	95%			2%	5%
	Food Waste + Manure	89%	95%			13%	20%
	Food Waste + Manure + Biosolids	89%	95%			25%	31%
	Biosolids + Manure + Yard Waste	89%	95%			14%	16%
	Biosolids + Manure + Yard Waste + Food Waste	89%	95%			27%	33%

(Continued.)

Table 3. (Continued.)

Technology	Waste Type	% yield N after treatment[a]	% yield of P after treatment[b]	kg CO_2 eq emissions/ kg N[c]	kg CO_2 eq emissions/ kg P[d]	Potential offset of US N demand[e]	Potential offset of US P demand[f]
Hydrothermal Carbonization	Food Waste	35%	83%	0.6	3.1	5%	14%
	Biosolids (Urine)	35%	83%	1.7	19.7	4%	6%
	Biosolids (Feces)	35%	83%	1.5	4.4	1%	3%
	Manure	35%	83%	2.1	3.8	0%	2%
	Yard Waste	35%	83%	3.2	10.5	1%	2%
	Manure + Yard Waste	35%	83%			1%	5%
	Food Waste + Manure	35%	83%			5%	17%
	Food Waste + Manure + Biosolids	35%	83%			10%	26%
	Biosolids + Manure + Yard Waste	35%	83%			5%	13%
	Biosolids + Manure + Yard Waste + Food Waste	35%	83%			11%	28%

[a] Danso-Boateng *et al* (2015), Gerner *et al* (2021), Li *et al* (2023), Melo *et al* (2019), McGaughy & Reza (2018); McIntosh *et al* (2022), Orner *et al* (2021), Paneque *et al* (2019), Zhang *et al* (2014).

[b] Li *et al* (2023), Melo *et al* (2019), McGaughy and Reza (2018); McIntosh *et al* (2022), Orner *et al* (2021), Paneque *et al* (2021).

[c] Owsianiak *et al* (2016), (Owsianiak *et al* 2018), Timonen *et al* (2019), Walling and Vaneeckhaute (2020).

[d] Owsianiak *et al* (2016), (Owsianiak *et al* 2018), Timonen *et al* (2019), Walling and Vaneeckhaute (2020).

[e] IFASTAT (2023), USDA ERS (2019), USDA (2017), Abd El Lateef *et al* (2021), Bernstad and la Cour Jansen (2011), U.S. Census Bureau QuickFacts: Ohio (2023), Fung *et al* (2019), Haouas *et al* (2021), Johansson *et al* (2001).; Langholtz *et al* (2016), Holtz and Culumber (2019), Pagliaccia *et al* (2019), Prado *et al* (2022), Rose *et al* (2015), Tahboub *et al* (2007), EPA (2017), (EPA 2022), Zhang *et al* (2007).

[f] IFASTAT (2023), USDA ERS (2019), USDA (2017), El Lateef EM *et al* (2021), Bernstad and la Cour Jansen (2011), U.S. Census Bureau QuickFacts: Ohio (2023); Fung *et al* (2019), Haouas *et al* (2021), Johansson *et al* (2001), Langholtz *et al* (2016), Holtz and Caesar-TonThat (2004), Holtz and Culumber (2019), Pagliaccia *et al* (2019), Prado *et al* (2022), Rose *et al* (2015), Tahboub *et al* (2007), EPA (2017), (EPA 2022), Zhang *et al* (2007).

Table 4. Nutrient mass available from food waste, yard waste, and biosolids at state (Ohio) and county (Athens) levels.

		Nitrogen mass (Mg y^{-1})[a]	Phosphorus Mass (Mg y^{-1})[b]	Potential GHGs displaced from N fertilizer production (Mg $CO_{2\,eq}$)[c]	Potential GHGs displaced from P fertilizer production (Mg $CO_{2\,eq}$)[d]
Ohio	Food Waste in 2010 (EPA 2011)	32 749	6015	112 294	16 173
	Food Waste in 2018 (EPA 2022)	57 742	10 605	197 991	28 516
	Manure	2970	1659	10 184	4,459
	Yard Waste	5829	1687	19 986	4,535
	Human Urine	47 297	4300	162 177	11 561
	Human Feces	6450	2150	22 115	5,780
Athens county	Food Waste in 2010 (EPA 2011)	219	70	752	189
	Food Waste in 2018 (EPA 2022)	387	124	1,327	334
	Manure	17	9	57	25
	Yard Waste	33	9	112	25
	Human Urine	265	24	908	65
	Human Feces	36	12	124	32

[a] Table 2.
[b] Table 2.
[c] Albaugh *et al* (2012), Brentrup *et al* (2016), Hoxha and Christensen (2019), Owsianiak *et al* (2016), (Owsianiak *et al* 2018), Timonen *et al* (2019), Walling and Vaneeckhaute (2020), Wood and Cowie (2004).
[d] Albaugh *et al* (2012), Brentrup *et al* (2016), Hoxha and Christensen (2019), Owsianiak *et al* (2016), (Owsianiak *et al* 2018), Timonen *et al* (2019), Walling and Vaneeckhaute (2020), Wood and Cowie (2004).

Table 5. Greenhouse gas (GHG) reduction potential by processing technology, with GHG offset calculated relative to synthetic fertilizer manufacturing.

Technology	Nutrient	Production GHG Emissions (kg $CO_{2\,eq}$ kg^{-1})[a]	Annual Fertilizer Consumption (Mg)[b]	Total GHG Emissions by Technology (Mg $CO_{2\,eq}$)[c]	GHG Offset (Mg $CO_{2\,eq}$)	Net GHG Emissions (Mg $CO_{2\,eq}$)
Synthetic Fertilizers	Nitrogen	3.43	11 347 070	38 908 156	0	38 908 156
Compost	Nitrogen	37.0	11 347 070	419 929 606	−38 908 156	381 021 449
Anaerobic Digestion	Nitrogen	3.63	11 347 070	41 161 430	−38 908 156	2253 274
Hydrothermal Carbonization	Nitrogen	1.23	11 347 070	13 935 879	−38 908 156	−24 972 278
Synthetic Fertilizers	Phosphorus	2.69	1718 170	4619 904	0	4619 904
Compost	Phosphorus	222	1718 170	382 358 856	−4619 904	377 38 952
Anaerobic Digestion	Phosphorus	21.8	1718 170	37 478 751	−4619 904	32 858 848
Hydrothermal Carbonization	Phosphorus	7.39	1718 170	12 689 047	−4619 904	8069 143

[a] Wood and Cowie (2004), Albaugh *et al* (2012), Brentrup *et al* (2016), Hoxha and Christensen (2019), Owsianiak *et al* (2016), (Owsianiak *et al* 2018), Timonen *et al* (2019), Walling and Vaneeckhaute (2020),.
[b] IFASTAT (2023), USDA ERS (2019), USDA (2017).
[c] Albaugh *et al* (2012), Brentrup *et al* (2016), Hoxha and Christensen (2019), Owsianiak *et al* (2016), (Owsianiak *et al* 2018), Timonen *et al* (2019), Walling and Vaneeckhaute (2020), Wood and Cowie (2004).

Table 6. Nutrient amount, value, and percentage of demand potentially met by organic wastes in the state of Ohio and Athens County.

Spatial scale	Nutrient	Annual consumption in agriculture (Mg)[a]	Market Value (2022 prices)[b]	Amount available from wastes (Mg)[c]	% Nutrient demand potentially met by wastes	Market value of nutrients in wastes (2022 prices)
Ohio	Nitrogen	240 385	\$ 396 524 524	131 664	50%	\$ 198 417 444
Ohio	Phosphorus	57 220	\$ 177 267 365	31 954	36%	\$ 6319 565
Athens	Nitrogen	175	\$ 288 754	737	421%	\$ 1215 809
Athens	Phosphorus	41	\$ 125 550	179	441%	\$ 554 170

[a] IFASTAT (2023), USDA ERS (2019), USDA (2017).
[b] Intratec (2023), IFASTAT (2023), Triple Superphosphate Spot Price (2023), US Urea Spot Price (2023), USDA ERS (2019), Schnitkey *et al* (2022).
[c] Table 4.

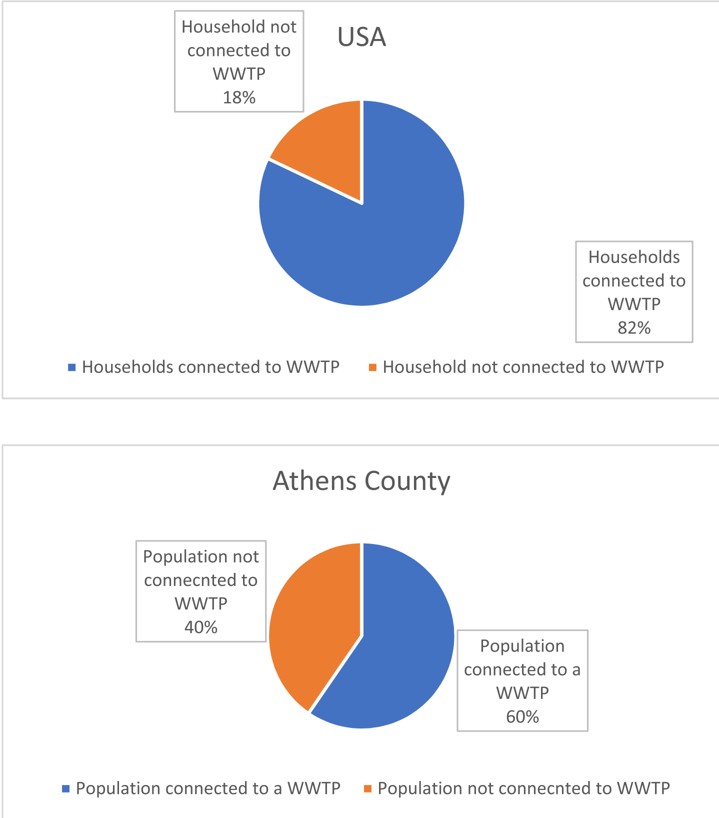

Figure 2. Proportion of biosolid nutrients that are constrained to HSTS (orange) or collected at WWTPs (blue) in the United States (upper panel) and in the Athens County, Ohio (lower panel).

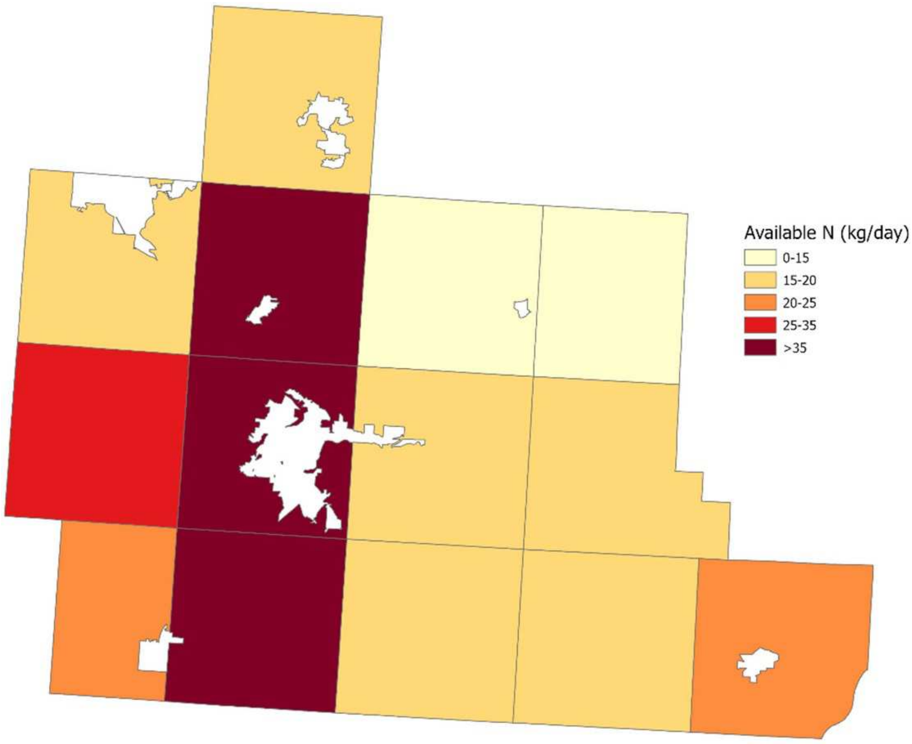

Figure 3. Heat map of nitrogen from home sewage treatment systems (HSTS) in Athens County, Ohio.

than would be required for composting, but they also have the potential to substantially reduce GHG emissions relative to synthetic fertilizers. There are more examples of AD at a variety of scales and applications to assess feasibility than there are for HTC.

The economic viability of AD depends on various factors including collection, transportation, conversion, biogas upgrading, and digestate application. In the US, the combined curb-side collection and transportation cost is around $2.27 per ton per km, which makes transportation of organic wastes beyond 25 km not economically viable (Hornbeg and Bhada-Tata 2012). The economic viability of the AD process itself depends on feedstock type, operating conditions, scale, and product end uses (e.g. combined heat and power, heating, cooking). From prior economic assessment work, feedstocks like the organic fraction of municipal solid waste and animal manures are economically viable at 2.5–25 tons per day when treated at thermophilic and mesophilic conditions, with pay back periods less than 10 years despite high capital expenses between $20–164 million (Rajendran *et al* 2014). In addition to nutrients in digestate, valorized in this study, revenue from biogas produced from AD accelerate the payback time for this technology. Wet digestate can either be dried or spread directly on farmland.

Hydrothermal carbonization (HTC) could be developed as a stand-alone technology or potentially used to treat wet digestate, converting it into solid fuel and fertilizer (Ipiales *et al* 2021). There are fewer examples of HTC in operation than AD, so economic analyses of HTC have greater uncertainty. An analysis of HTC development at a small-scale to process septage in Athens County, OH concludes that capital investment would range from $500 000 to $870 000 with a payback time of less than 7 years (Saha *et al* 2021). Other studies evaluating the economic feasibility of HTC estimated costs for large-scale systems that operate alongside an AD system. One should note that adding another process could add processing cost. For instance, the processing cost of AD of sewage sludge was reported as $70 per ton of sludge, whereas HTC of digestate added an additional $30 per ton of sludge (Medina-Martos *et al* 2020). Although the process cost is higher with integrated AD-HTC process ($100 per ton), the hydrochar product value in this case should exceed the cost and make the overall economics viable. It can be noted that hydrochar made from digestate as solid fuel does not compete with coal due to its low calorific value and high ash, however, AD-HTC for nutrient recovery has been reported as a profitable and ecofriendly approach (Bevan *et al* 2021).

With the value of synthetic fertilizers increasing dramatically in recent years, e.g. 42% increase in nitrogen fertilizer costs per unit between 2015 and 2022 (table 1), the time for return on investment in these operations will be shorter than it would have been a decade ago. Some regions of the US may be more suited to developing these technologies; in some cases, existing infrastructure for handling waste at WWTPs may be useful for co-locating AD and/or HTC. In other locations, where infrastructure is not in place and there are a greater number HSTS, there are greater environmental and human health benefits associated with implementation.

Taking full advantage of nutrients in waste from the human food system will require public acceptance of the use of biosolids for fertilizer. There are many fertilizer products that include biosolids, but they are not marketed as such, and public perception of using human waste in food agriculture is not wholly positive. Technologies like HTC involve high temperature treatments that kill pathogens and eliminate human health risks associated with biosolids (e.g. McGaughy and Reza 2018), so negative public perception is not based on actual risk. In larger cities, there may be greater risk of heavy metals entering large sewer systems, but these can be monitored, and monitoring is required as a condition of permits. For small communities, the risk of metal contamination in waste may be lower.

It should be noted that organic waste resources extend beyond those that are associated with the human food system. The scope of this study was limited to the food system in order to assess the potential of a circular nutrient economy and improved nutrient use efficiency by humans. Forestry and landscaping waste could supply additional nutrients from waste (Langholtz *et al* 2016), but the concentration of nitrogen and phosphorus is lower relative to food waste or biosolids. Due to the greater carbon content of forestry waste, these could potentially be co-digested in AD with high nutrient food wastes and biosolids. The addition of carbon may improve the biogas quality and potential energy generation of AD (e.g. Herman *et al* 2022).

Although the focus of this study was on nutrient recapture for fertilizer, the AD process is also useful to generate fuel in the form of biogas, which can be used as a substitute for natural gas (Bracmort 2011). The added benefit of energy generation could improve the financial value of this technology in some cases, and the fuel displacement would enhance the GHG emission mitigation of this technology. The value added by coproducing fuel and fertilizer can offset the need for fossil fuel combustion (natural gas use and fertilizer manufacturing).

5. Conclusion and recommendations

Human nutrient use efficiency could be dramatically improved by repurposing organic wastes from human food systems for fertilizers. In the US, the amount of nutrients in food wastes and biosolids primarily could offset up to 11%–27% of nitrogen requirements in agriculture. If these wastes are processed through HTC, there would be 64% reduction in GHG emissions relative to fertilizer manufacturing. While these gains are notable, opportunities for improved nutrient use efficiency in some rural regions with small-scale agricultural operations are much greater. For instance, in Athens County, Ohio, a circular economy of nutrients is achievable, with waste nutrients meeting all of the fertilizer demand and an excess of nutrients produced for external markets. Further development of technologies is need to realize a circular economy with nutrients from waste. The value proposition of repurposing nutrients in wastes varies by location, but there are economic, environmental, and health benefits evident at all geographic scales analyzed by this study.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Public data sources used for spatial analysis

https://gis.dot.state.oh.us/tims—GIS data for cities, townships (TIMS)
https://data.census.gov/cedsci/—2020 Census population data from ACS
www.usgs.gov/centers/eros/science/national-land-cover-database—National Landcover Database used for farm and pasture data

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