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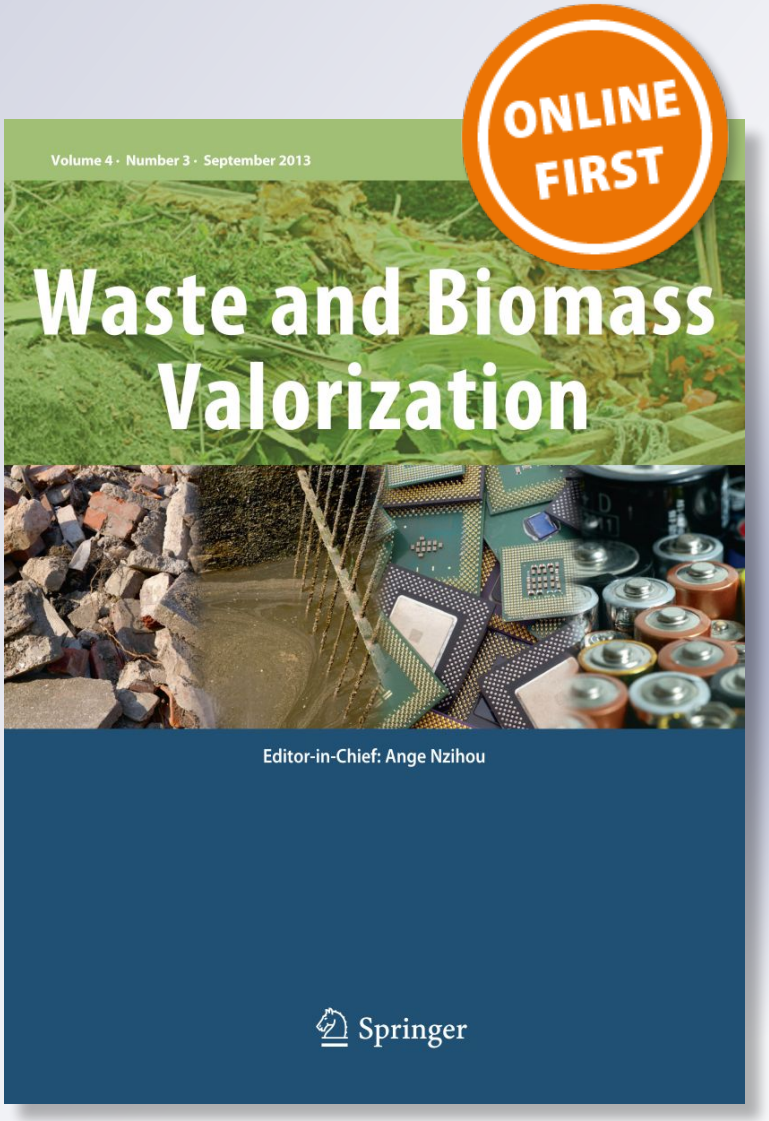

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SHORT COMMUNICATION

Nutrient and Pathogen Suppression Properties of Anaerobic Digestates from Dairy Manure and Food Waste Feedstocks

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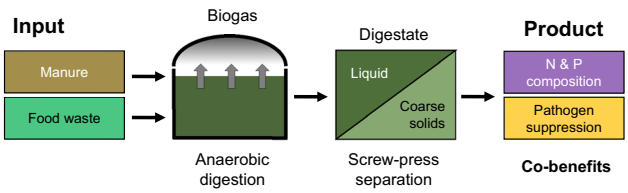
Abstract

Anaerobic co-digestion of dairy manure and food wastes is increasing in the New England region of the United States because of policy measures intended to divert organic materials from landfills, reduce greenhouse gas emissions, and increase renewable biogas energy production. The sustainability of this approach depends on the management and valorization of remaining solid and liquid residues (i.e., digestates) after anaerobic digestion. Few studies have characterized digestates derived from combined dairy manure and food waste feedstocks. In this study, we analyzed screw-press separated liquid and solid digestates from 6 of 26 (23%) operational full-scale facilities in New England. We quantified multiple pools of nitrogen and phosphorus in these materials, with results suggesting that, in most cases, these nutrients largely exist in forms that can be recycled via slow-release fertilization, with smaller fractions in forms more easily lost to the environment. Furthermore, we found that solid digestates can inhibit mycelial growth of a common soilborne fungal pathogen, *Rhizoctonia solani*, suggesting potential to manage resident soil pathogens. Capitalizing on both nutrient recycling and pathogen suppression co-benefits will likely be useful in digestate valorization efforts.

Graphic Abstract



Keywords Nitrogen · Phosphorus · Nutrient recovery and recycling · Biogas residues · Anaerobic co-digestion · Digestate · Pathogen suppression

Statement of Novelty

We provide detailed N and P composition data for digestates derived from dairy manure and food waste feedstocks and novel information on the pathogen suppression potential of coarse solid digestates.

Introduction

Anaerobic digestion (AD) is the process of microbial decomposition of organic substrates in the absence of oxygen [1]. Operations facilitating AD of organic wastes

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can be designed to be either mesophilic or thermophilic. Although thermophilic conditions are generally more effective at removing pathogens, reducing odor emissions, and increasing rates of organic matter degradation [2], mesophilic conditions are preferred for treating animal manure because of a greater robustness of the process [3]. AD can be used to process a wide range of organic materials, including animal manure, crop residues, food processing wastes, post-consumer food scraps, and municipal sewage sludge [4]. Goals of AD include reduction of greenhouse gas emissions to the environment and recovery of resources from organic wastes, including nutrients and methane-enriched biogas [1].

Methane production and capture for use as renewable energy is optimized by manipulating the biodegradability of the influent feedstock [5, 6]. For example, dairy manures are relatively high in recalcitrant carbon and have small (< 10) C:N ratios [7], resulting in low methane yield [8, 9]. "Food waste" encompasses a wide range of materials of both animal and plant origin diverted from food processing and post-consumer sources. Compared to dairy manure, food wastes contain more easily degraded carbon with a higher C:N ratio than is found in dairy manure [10]. AD of food waste alone generates ammonia gas that destabilizes digester reactions [7, 11, 12]. Co-digestion of dairy manure and food wastes can both increase biogas production and improve process stability [7, 12] and is, therefore, an attractive strategy in the context of policies aiming to divert food wastes from landfills in the New England region of the United States (U.S.) and elsewhere (e.g., Vermont Act 148).

In addition to biogas, AD produces residues, or digestates, that can be used as fertilizer, soil amendment products, animal bedding [13–17], or substrates for edible mushroom cultivation [18]. Digestate characteristics are influenced by the properties of the feedstock [19–21], as well as the AD process, parameterization, and reactor type [22–24]. Digestates can be separated into solid and liquid fractions with different physicochemical and biological profiles, which determine their agronomic value and environmental risk [13–16, 25]. Mechanical screw-press separators are the most common method of solid–liquid separation used on manure digesters [15, 16, 25]. Solid digestates (i.e., coarse solids) are generally > 20% dry matter and contain recalcitrant lignocellulosic biomass not degraded under AD conditions [26]. Solid digestates are more economical to transport than liquid material [27], and are usable as a soil amendment to increase plant growth [15, 16] and stimulate soil microbial activity [19]. Post-screw press liquid digestates are typically applied as fertilizer for feed crops or pasture fields adjacent to digesters and may pose a similar eutrophication risk to using raw manure as fertilizer over time, depending on management strategy [28]. Technologies, including dissolved air flotation (DAF) and centrifugation, can be used to process post-screw press liquid digestates and capture fine solids not removed by screw press (e.g., [29]).

Characterization of digestates derived from combined dairy manure and food waste feedstocks remains uncommon (Table S1), which limits information available for various analyses (e.g., modeling) and product development. Furthermore, often only bulk (i.e., total) measures of nitrogen (N) and phosphorus (P) contents are reported, and liquid and solid digestate fractions are rarely assessed. Some studies quantify multiple forms of nitrogen (e.g., NH_4–N and organic N) (Table S1), but do not consider N stability during material handling, and very few have examined multiple measures of P [30]. Understanding N and P forms and stability within digestates is important to: (a) better predict material usefulness as a nutrient source to plants through time [31], (b) indicate potential nutrient losses to the environment via volatilization or leaching [28], and (c) identify nutrient pools to target for nutrient recovery strategies [32]. A potential important co-benefit of recycling nutrients in digestate is pathogen suppression, specifically biocontrol of *Rhizoctonia solani*, a pathogenic root fungus which negatively affects crop production worldwide [33].

Our objectives in this study were to: (a) quantify the N and P compositions of screw-press separated liquid and solid digestates from 6 of 26 (23%) full-scale operational facilities in the New England region, and (b) test an alternative use for coarse solids as a biocontrol treatment for *Rhizoctonia solani*.

Materials and Methods

Digester Selection

We sampled six full-scale mesophilic (37–40 °C) manure digesters equipped with screw-press solid–liquid separators in Sept–Oct 2017 with permission from farmers/operators. We obtained information on digester characteristics through the EPA AgSTAR Database [34], state regulatory agencies, and farmer/operator interviews. Dairy manure was a feedstock at all sites, ranging from 18 to 100% of total annual feedstock among the six digesters (Table 1). Various "food wastes" (including source separated organics and/or food processing residuals) were co-digested at five sites ranging from 1 to 39% of total annual feedstock and included whey waste water and dairy process waste, source separated organics, and brewery waste (Table 1). Other feedstocks included fats, oils, and grease (FOG), glycerin, dissolved air flotation sludge (DAF), recycled digester effluent, and < 1% other additives used to stabilize internal digester conditions.

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Table 1 Feedstocks for six full-scale mesophilic anaerobic digesters in New England as reported by farmer-operators

Digester	Type	Co-digestion feedstocks (% annual total)	% Food waste[a]	% Dairy manure
A	Mixed plug flow	100% dairy manure	0	100
B	Mixed plug flow	99% dairy manure, 1% whey waste water	1	99
C	Mixed plug flow	99% dairy manure, 1% whey waste water	1	99
D	Complete mix	18% dairy manure, 33% source separated organics, 20% FOG, 21% DAF, 6% dairy process waste, 2% glycerin	39	18
E	Complete mix	53% dairy manure, 35% source separated organics, 6% FOG, 4% DAF, 1% glycerin, < 1% other	35	53
F	Complete mix	54% dairy manure, 23% brewery waste, 13% dairy process waste, 3% glycerin, 3% effluent, 2% FOG, 2% source separated organics, < 1% other	38	54

FOG fats, oils, grease; *DAF* dissolved air-flotation sludge

[a]"Food waste" includes source separated organics, dairy process waste, brewery waste, and whey waste water

Digestate Sampling

We collected five equivalent subsamples of liquid digestate (LD) and solid digestate (SD) in parallel following screw-press separation at 15-min intervals over the course of 1-h and mixed separately to form a composite LD sample and a composite SD sample for each digester. We then divided the composite LD sample into two 1-L subsamples stored in brown polyvinyl bottles, transported on ice, and then frozen until analysis of P content and physiochemical properties. For the composite SD sample, we immediately froze 1 L to preserve for inorganic N analysis, and then spread a larger amount (~55 L) evenly in a plastic tray 15 cm deep, where it cured passively for 45 days in a greenhouse (13–27 °C) before additional physicochemical analysis. We intended for the curing period to simulate farm management practice, which allows for passive composting and air-drying under cover before solids are recycled as animal bedding on the farm or sold as an amendment product. After the curing period was complete, we homogenized SD samples by hand and placed three representative 1-L subsamples in frozen storage for additional physicochemical analysis. We previously describe some basic characteristics of cured solid digestate for Digesters A and E in [18], but provide new additional data for those materials here.

Physicochemical Characteristics

Physicochemical characteristics measured included total solids, total volatile solids, pH, conductivity, and total carbon at the University of Maine [35]. Total solids for liquid and solid digestates were determined gravimetrically. Dry materials (for solid digestates only) were then combusted for 6 h at 550 °C to determine total volatile solids as mass loss on ignition. Total carbon (for solid digestate only) measurements were made by dry combustion and analysis using a Leco CN-2000.

Nitrogen Analyses

For liquid digestate, total Kjeldahl N (TKN) was measured by sulfuric acid digestion, heat distillation, and titration with NaOH. NH_4–N was quantified using a 1 M KCl extraction followed by colorimetric analysis. We estimated organic N as the difference between TKN and NH_4–N. We assumed that TKN values were representative of total N in liquid digestates and NO_3–N was negligible because we expect anaerobic conditions within the digesters to inhibit nitrification.

For cured solid digestates, extractable NH_4–N and NO_3–N were determined at the University of Maine from 5 g dried and sieved (< 2 mm) samples in 50 mL of 1 M KCl (1:10 solids:solution ratio). Extract solutions were vacuum filtered (0.45 µm) before determination by colorimetric analysis using an O.I. Alpkem A/E ion analyzer. We extracted NH_4–N and NO_3–N in duplicate from fresh solid digestate using an identical extraction protocol, diluted below 10 ppm, and analyzed samples using methods described in [36] and [37], respectively, with a BioTek Synergy HT microplate reader. TKN for fresh solid digestate materials was measured using the same methods applied for liquid digestates and we again assumed that organic N was the difference between TKN and NH_4–N. We calculated total N for solid digestates as the sum of TKN + NO_3–N.

Phosphorus Analyses

In addition to the bulk measure of total P, we used three P extractions to quantify different pools of P ranging from soluble/mobile to plant-accessible to stable in liquid and cured solid digestate materials. Water-extractable P, which can include soluble reactive P and dissolved organic P, is considered a proxy for the most readily available P fraction and poses the greatest risk of leaching [38]. Olsen P and 2% citric acid extractable P have been shown to serve as

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effective proxy measures for P fractions likely to become accessible to plants [30, 31, 39]. We assume that any P extracted by the Olsen test is also extracted with 2% citric acid.

For liquid digestates, we developed an extraction protocol that identifies the following pools of P: (a) water-extractable soluble reactive P, (b) water-extractable P of other forms (e.g., dissolved organic P), (c) total P of centrifuge-separated fine solids, (d) Olsen P of centrifuge-separated fine solids, and (e) 2% citric acid extractable P of centrifuge-separated fine solids. To determine water-extractable P, we diluted 2 g dry mass equivalent liquid digestate samples 1:100 with deionized water, placed on a shaker for 1 h, and centrifuged for 20 min at 4066×*g* [38]. We decanted an aliquot of the unfiltered sample and analyzed it for total P [40]. We filtered a second portion (0.45 µm) and analyzed this sample for orthophosphate by colorimetry (details below). We then homogenized the residual separated fine solids, determined % moisture based on remaining mass, and performed Olsen P and 2% citric acid extractions in parallel. We obtained Olsen P from 0.5 g dry mass equivalent fine solids extracted with 0.5 M $NaHCO_3$ adjusted to pH 8.5 to achieve a solids:solution ratio of 2:40 with a shaking time of 0.5 h [39]. For 2% citric acid extractions, we used 0.5 g dry mass equivalent fine solids sample extracted with 2% citric acid solution to attain a solids:solution ratio of 1:100 with a shaking time of 1 h [30]. We sent a third sample of residual fine solids to University of Maine for total P analysis (1 g dried ground sample combusted at 550 °C for 6 h and extracted in a 50% HCl solution, after which P was measured, in accordance with EPA Acid Digestion Method 3051).

For solid digestates, total P in cured solids was determined at University of Maine using the same method described for fine solids above, and we measured water-extractable P, Olsen P, and 2% citric acid extractable P in parallel. We obtained water-extractable P by adding deionized water to 1 g dry weight equivalent sample to achieve a solids:solution ratio of 1:100 and shaking on a horizontal shaker for 1 h [38]. We performed Olsen P (2 g dry mass equivalent solid digestate, 2:40 solids:solution ratio, shaking time = 0.5 h) and 2% citric acid extractable P (1 g dry mass equivalent SD, 1:100 solids:solution ratio, shaking time = 1 h) extractions for cured solid digestate using the solutions described above. We conducted all water-extractable P, 2% citric acid extractable P, and Olsen P extractions in duplicate, with extracts filtered (0.45 µm), diluted to < 1 ppm, and analyzed for orthophosphate using the malachite green method [41]. We adjusted dilutions of Olsen P extracts to pH 7 with 1 drop 10% H_2SO_4 so they would not react with acidic ammonium paramolybdate solution in plate wells. We read samples in triplicate on plates at 630 nm using a BioTek Synergy HT microplate reader with a detection limit < 0.02 ppm.

Other Nutrients

One-gram dried ground sample was combusted at 550 °C for 6 h at the University of Maine and extracted in a 50% HCl solution, after which B, Ca, Cu, Fe, K, Mg, Mn, Na, total P, and Zn were measured in accordance with EPA Acid Digestion Method 3051.

Plate Competition Assay

We tested fresh and cured SD samples from digesters B, C, D, and F for suppression of fungal pathogen *Rhizoctonia solani* using an agar plate competition assay [42, 43]. Briefly, we added independent pairs (reference and test) of 0.5 g of each SD material (fresh and cured) to 10 mL of sterile water in 25 mL test tubes then shaken overnight. The next day, we prepared a pair of conical flasks per sample containing 1.5 g agar in 90 mL deionized water. We poured the reference pair member into one flask and both flasks were autoclaved for 30 min. We added the test pair member to water agar after the mixture had cooled to 45 °C. Next, we gently swirled the contents of both the reference (non-living microbes) and test (living microbes) gently to mix, and poured them into 100 mm × 15 mm plastic petri plates. Once the agar hardened, we transferred plugs of *R. solani* growing on potato dextrose agar onto the surface of each plate and then incubated at room temperature for 24 h. We recorded three of the longest mycelium radii to the nearest mm, and used the mean as a representative measure to compare suppressive potential among different digestate samples. We quantified suppression of *R. solani* as the reduction in growth between test and reference plates.

Results and Discussion

Physicochemical Characteristics of Digestates

Liquid and fresh solid digestates contained a range of 2.2 to 5.1% and 21.5 to 33.2% total solids, respectively (Table 2). A 45-day curing period for solid digestate materials increased total solids to 28.4 to 40.8%, which was mostly organic matter (total volatile solids = 23.7 to 35.5%, total carbon = 41.1 to 46.5% of dry matter). Cured solid digestate materials from digesters accepting ≤ 1% food waste (A–C) had pH values in the narrow range of 8.4 to 8.5, whereas cured solid digestate materials from digesters accepting more diverse feedstocks (D–F) exhibited lower pH values (7.3 to 7.9) (Table 2). These pH values support prior reports for digestates, ranging from 7.3 to 9.0 [22].

Digester E had the greatest cured solid digestate conductivity at 7 mmhos cm^{-1}, while all other cured solid digestate materials were in the range of 2.5 to 4.3 mmhos cm^{-1}.

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Table 2 Physicochemical characteristics of liquid digestates (LD) and solid digestates (SD). SD characteristics for Digesters A and E were initially reported in [18]

Digester	LD TS (%)	Fresh SD TS (%)	Cured SD TS (%)	Cured SD TVS (%)	Cured SD total C (% dry matter)	Cured SD C:N ratio	Cured SD pH	Cured SD conductivity (mmhos cm^{-1})
A	3.2	27.5	34.0	30.3	44.7	17.7	8.4	2.5
B	4.1	33.2	40.8	35.5	42.7	20.5	8.5	2.8
C	4.1	31.2	38.1	32.8	42.4	18.0	8.4	4.3
D	2.2	24.1	32.9	30.6	46.5	23.6	7.3	2.7
E	5.1	21.5	28.4	23.7	41.1	16.6	7.9	7.0
F	3.0	27.9	37.4	33.3	44.6	19.4	7.4	3.1
Mean ± standard deviation	3.6 ± 1.0	27.6 ± 4.3	35.3 ± 4.4	31.0 ± 4.1	43.7 ± 2.0	19.3 ± 2.5	8.0 ± 0.5	3.7 ± 1.7

Salts in some digestate products may pose limitations for soil application due to plant sensitivities. However, there is little agreement on how to classify salts in organic amendments and what, if any, limits should be set [44]. The University of Maine Soil Testing Lab recommends that final compost blends with soil or container media/potting mixes have conductivity values < 4 mmhos cm^{-1}. Digestion operations increasing their food waste intake should monitor conductivity in digestate products to aid the design of effective products. For nutrients, we describe N and P results below, while data for other nutrients can be found in the supplementary materials (Table S2).

Nitrogen Composition of Digestates

Organic N accounted for 50–66% of total N in liquid digestate samples (Table 3), indicating that these materials offer a mixture of readily plant-available inorganic N and organic N (Fig. 1a). Organic N forms are likely to become available to plants more slowly. Efficient recycling of liquid digestate N to crops will depend on aligning N availability with crop demand and limiting N losses to the environment. The large fraction of N existing as NH_4^+ indicates risk of ammonia volatilization, depending on application timing and method. Further research is needed on this topic.

Total N ranged from 19.6 to 56.2 g N kg^{-1} fresh solid digestate on dry basis, although curing reduced differences between materials as shown by more similar N contents after curing (Table 4). Results for cured solid digestate materials revealed that N loss occurred during 45-day curing period in four of six samples and was especially pronounced (28–60% N loss) for two of the samples, both containing substantial food waste in their feedstocks (Fig. 1b, c). This reduces the amount of N available for recycling into crops. Relatively high N loss could be the result of differences in N content of influent feedstocks and may also be influenced by digester designs, e.g., complete-mix versus plug-flow. Model simulations have suggested that plug-flow reactors produce lesser effluent concentrations of total N compared to complete-mix units [45]. In our study, N loss during curing appears to have been driven by volatilization of ammonia (NH_4^+ to NH_3) or coupled mineralization-volatilization (organic N to NH_4^+ to NH_3) (Fig. 1b, c). The latter is supported by the fact that the total N reduction exceeds the inorganic N measured in the

Table 3 Nutrient composition of liquid digestates (LD)

Parameter	Mean ± standard deviation
Total N (g N kg^{-1} LD)	3.3 ± 1.0
NH_4–N (g N kg^{-1} LD)	1.4 ± 0.4
Organic-N (g N kg^{-1} LD)	1.9 ± 0.6
Total P (g P kg^{-1} LD)	0.47 ± 1.6
Water-extractable P (SRP) (g P kg^{-1} LD)	0.05 ± 0.02
Water-extractable P (other forms) (g P kg^{-1} LD)	0.04 ± 0.03
Olsen P of fine solids (g P kg^{-1} LD)	0.05 ± 0.02
[2% citric acid P–Olsen P] for fine solids (g P kg^{-1} LD)	0.24 ± 0.09
P in fine solids not extracted by 2% citric acid (g P kg^{-1} LD)	0.09 ± 0.03
[2% citric acid P in fine solids–water-extractable P (all forms)] (g P kg^{-1} LD)	0.20 ± 0.10

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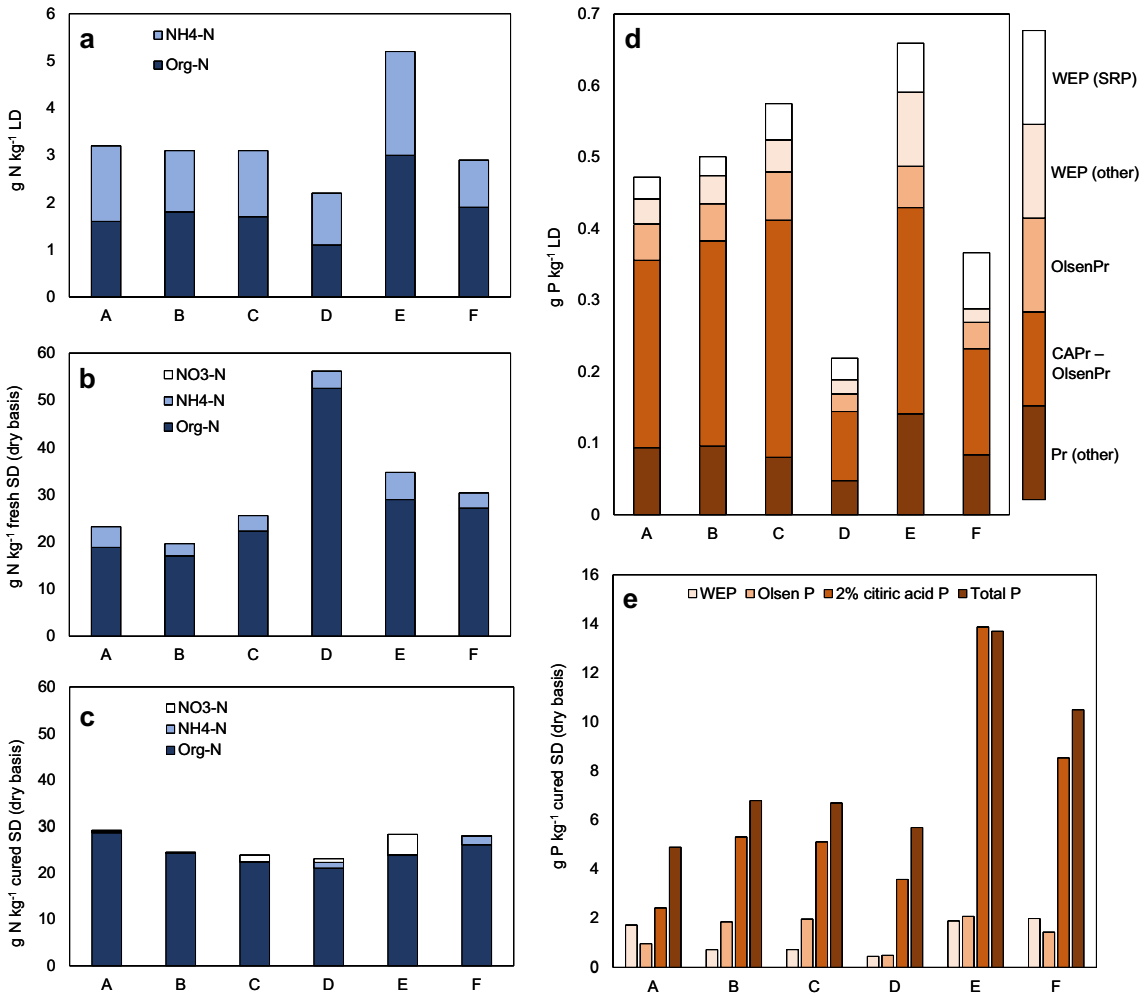

Fig. 1 Nitrogen (**a**–**c**) and phosphorus (**d**–**e**) composition of liquid digestates (LD) and solid digestates (SD). Total N, NO_3–N, NH_4–N, organic N, and Total P for cured SD were initially reported in [18] for Digesters A and E only. *WEP* water-extractable P. *CAP* 2% citric acid extractable P. Pr in (**d**) denotes P forms in residual fine solids of liquid digestate post-centrifugation

initial fresh solid digestate for some samples. We observed traceable NO_3–N in all cured solid digestate materials, providing evidence for nitrification during the curing process (Table 4). C:N ratios in cured solid digestate ranged from 15:1 to 21:1 across all six materials (Table 2), indicating potential for further N mineralization in some materials, which would increase the bioavailability of N in these solid digestate materials over time.

Phosphorus Composition of Digestates

Total P in liquid digestates ranged from 0.22 to 0.66 g P kg^{-1} liquid digestate with a mean of 0.47 ± 0.16 g kg^{-1} (Table 3). Across liquid digestate samples, P contained within centrifuge-separated fine solids accounted for 73–87% of total P (Fig. 1d). Olsen extractions liberated 12–15% of the P in liquid digestate centrifuge-separated fine solids, and an additional 55–69% on top of that was extracted by 2% citric acid, indicating that the majority of P contained in liquid digestate fine solids is in forms likely to become plant-available over time [30] (Table 3). Water-extractable P accounted for 13–27% of total P in liquid digestate and included a mixture of soluble reactive P and other forms (e.g., dissolved organic P) (Fig. 1d). We propose that the P liberated from fine solids by 2% citric acid P minus water extractable P (including soluble reactive P and other forms) is a metric that indicates the presence of slow-release P. This metric equaled 41 ± 14% of total P in liquid digestates (Table 3). Previous authors have reported that water-extractable P is a good predictor of short-term P fertilization effect [30, 46]; however, this form of P is also likely to be more readily lost to the environment via leaching or runoff [28, 38]. Therefore, we hypothesize that, over repeated applications to soils, digestate materials that contain a greater proportion of slow-release P (as defined here) may enable more

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Table 4 Nutrient composition of solid digestates (SD)

Parameter	Mean ± standard deviation
Fresh solids (dry basis)	
Total N (g N kg^{-1} fresh SD)	31.6 ± 13.2
NH_4–N (g N kg^{-1} fresh SD)	3.8 ± 1.1
NO_3–N (g N kg^{-1} fresh SD)	0.0 ± 0.0
Organic-N (g N kg^{-1} fresh SD)	27.8 ± 13.0
Cured solids (dry basis)	
Total N (g N kg^{-1} cured SD)	26.1 ± 2.7
NH_4–N (g N kg^{-1} cured SD)	0.6 ± 0.8
NO_3–N (g N kg^{-1} cured SD)	1.2 ± 1.7
Organic-N (g N kg^{-1} cured SD)	24.3 ± 2.7
Total P (g P kg^{-1} cured SD)	8.1 ± 3.4
Water-extractable P (g P kg^{-1} cured SD)	1.3 ± 0.7
Olsen P (g P kg^{-1} cured SD)	1.5 ± 0.6
2% citric acid P (g P kg^{-1} cured SD)	6.5 ± 4.2
[2% citric acid P–water-extractable P] (g P kg^{-1} cured SD)	5.2 ± 3.8

Units are on a dry matter basis

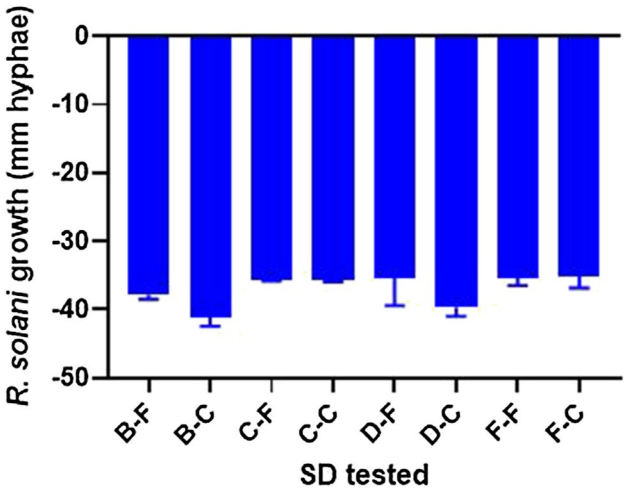

Fig. 2 Plate competition assay measuring hyphal growth of *Rhizoctonia solani* on solid digestate (SD) water extract agar from farms B, C, D, & F, including fresh (F) and cured (C) SD. Illustrated are means ± 1 standard error of the change from autoclaved control. X-axis labels indicate farm ID and fresh vs. cured SD (e.g., B-F is farm B - fresh SD). Both controls and treatment comparisons were inoculated with virulent *Rhizoctonia solani*

efficient recycling of P from digestates to crops. Further experimentation is needed to test this hypothesis.

For cured solid digestate materials, total P ranged widely from 4.9 to 13.7 g P kg^{-1} dry solid digestate with a mean ± standard deviation equal to 8.1 ± 3.4 g P kg^{-1} dry solid digestate (Table 4). Approximately 8–35%, 9–29%, and 49–100% of the total P contained within cured solid digestate materials was water-extractable, Olsen-extractable, and 2% citric acid-extractable, respectively (Fig. 1e). These results suggest that the majority of P contained in cured solid digestate materials is not immediately bioavailable or leachable, but is likely to become available to plants in the future. Similar to liquid digestates, we propose that the difference between 2% citric acid P and water-extractable P, which accounted for 59 ± 14% of total P, is likely an indicator of slow-release P that can be tested in subsequent studies of digestate as a fertilizer. Total P was a poor predictor of water-extractable P ($r^2 = 0.38$, $P = 0.19$) or Olsen P ($r^2 = 0.33$, $P = 0.23$), indicating that total P measurements included in conventional compost tests may not be good predictors of leaching or immediate plant-availability of P in solid digestate. However, 2% citric acid P and our proposed slow-release P metric were predicted well by total P ($r^2 = 0.98$, $P < 0.001$ and $r^2 = 0.68$, $P < 0.045$, respectively), suggesting that total P results do provide a meaningful measure of P likely to become more slowly plant-available in solid digestate materials over time.

Other Nutrients

Data for other nutrients are contained in the supplementary materials (Table S2).

Plate Competition Assay

Growth of *R. solani* was reduced in cultures containing test coarse solid digestate compared to corresponding reference (autoclaved) cultures for all materials tested (Fig. 2). Both fresh and cured solid digestate materials from facilities B, C, D, and F are likely to contain microbes which, through competitive advantage, may act as pathogen suppressants of *R. solani*. Cured SD showed greater suppression of *R. solani* than fresh SD for digesters B and D (Fig. 2). This finding is supported by other studies that suggest more mature composts are more suppressive than immature composts, due in part to lower concentrations of labile carbon which favor pathogens, and the presence of microbial consortia which may act as biocontrol [42].

Conclusions

Our results provide a detailed picture of N and P compositions in both liquid and solid anaerobic digestates derived from dairy manure and food waste feedstocks, contributing to recent research on digestate nutrient recovery and characterization [47]. Nutrients contained in these digestate materials can be expected to largely become bioavailable

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over time, providing fertility benefits in soil management or greenhouse crop production. However, we also identified forms of N and P that are more likely to be lost to the environment, which will present challenges in the pursuit of efficient nutrient recycling from digestate to crops. Further experimentation, ideally over longer times than commonly employed in short-term bioassays, is needed to test our proposed slow-release P metric. In addition, our results suggest solid digestate products contain active microbial communities that inhibit fungal pathogens including *R. solani*. Future work should examine microbial community composition and succession within solid digestate products to determine optimal use for biocontrol. Ultimately, digestate valorization efforts that bundle nutrient recycling with co-benefits such as pathogen suppression may prove more successful.

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