Nutrient and pathogen suppression properties of anaerobic digestates from dairy manure and food waste feedstocks

Short Communication

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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.

KEYWORDS

nitrogen, phosphorus, nutrient recovery and recycling, biogas residues, anaerobic co-digestion, digestate, pathogen suppression

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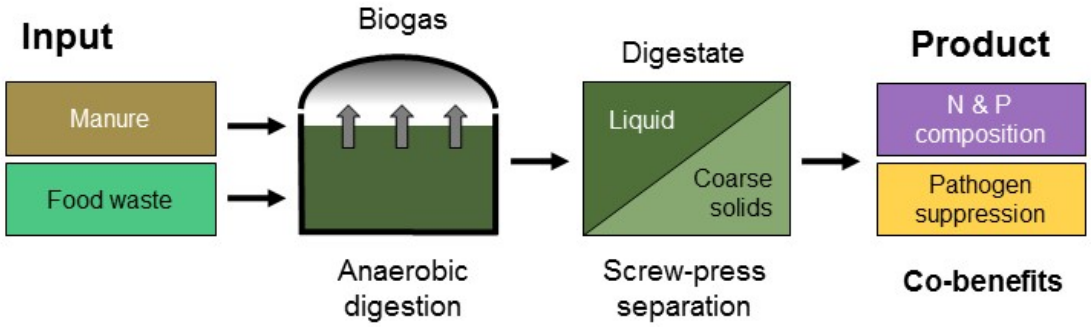
GRAPHICAL ABSTRACT



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.

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1. INTRODUCTION

Anaerobic digestion (AD) is the process of microbial decomposition of organic substrates in the absence of oxygen to generate methane biogas for energy production [1]. Operations may be designed as 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 process a wide range of organic materials, including animal manure, crop residues, food processing wastes, post-consumer food scraps, and municipal sewage sludge [4]. Methane production is the primary goal, which 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. 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

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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 fail to 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 of material usefulness as a nutrient source to plants through time [31], (b) serve as an indicator of potential nutrient losses to the environment via volatilization or leaching [28], and (c) identify nutrient pools to target for nutrient recovery

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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*.

2. MATERIALS AND METHODS

2.1. 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 18-100% 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 1-39% 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.

2.2. 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 one-hour and

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mixed separately to form a composite liquid sample and a composite solid sample for each digester. We then divided the composite liquid 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. Likewise, we divided the composite solid sample into two 1-L subsamples, of which we immediately froze one to preserve for inorganic N analysis, and the spread the second 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 solid digestate 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.

2.3. 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 hrs 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.

2.4. Nitrogen analyses

For liquid digestate, total Kjeldahl N (TKN) was measured by sulfuric acid digestion, heat distillation, and titration with NaOH and NH_4-N was quantified using a 1 *M* KCl extraction

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160 followed by colorimetric analysis. We estimated organic N as the difference between TKN and
161 NH_4-N. We assumed that TKN values were representative of total N in liquid digestates and
162 NO_3-N was negligible because we expect anaerobic conditions within the digesters to inhibit
163 nitrification.

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

175 **2.5. Phosphorus analyses**

176 In addition to the bulk measure of total P, we used three P extractions to quantify
177 different pools of P ranging from soluble/mobile to plant-accessible to stable in cured liquid and
178 solid digestate materials. Water-extractable P, which can include soluble reactive P and dissolved
179 organic P, is considered a proxy for the most readily available P fraction and poses the greatest
180 risk of leaching [38]. Olsen P and 2% citric acid extractable P have been shown to serve as
181 effective proxy measures for P fractions likely to become accessible to plants [30-31,39]. We
182 assume that any P extracted by the Olsen test is also extracted with 2% citric acid.

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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 hr, and centrifuged for 20 min at 4066 x *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 hr [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 hr [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 hr [38]. We performed Olsen P (2 g dry mass equivalent solid digestate, 2:40 solids:solution ratio, shaking time = 0.5 hr) and 2% citric acid extractable P (1 g

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dry mass equivalent SD, 1:100 solids:solution ratio, shaking time = 1 hr) extractions for cured solid digestate using the solutions described for liquid digestate 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.

2.6. 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.

2.7. 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

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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.

3. RESULTS AND DISCUSSION

3.1 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-d 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}. 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

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252 products to aid the design of effective products. For nutrients, we describe N and P results below,
253 while data for other nutrients can be found in the supplementary materials (Table S2).

254 **3.1. Nitrogen composition of digestates**

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

262 Total N ranged from 19.6-56.2 g N kg^{-1} fresh solid digestate on dry basis, although curing
263 reduced differences between materials as shown by more similar and consistent N contents after
264 curing (Table 4). Results for cured solid digestate materials revealed that N loss occurred during
265 45-d curing period in four of six samples and was especially pronounced (28-60% N loss) for
266 two of the samples, both containing substantial food waste in their feedstocks (Figure 1b and 1c).
267 This reduces the amount of N available for recycling into crops. Relatively high N loss could be
268 the result of differences in N content of influent feedstocks and may also be influenced by
269 digester designs, e.g., complete-mix plug-flow. Model simulations have suggested that plug-flow
270 reactors produce smaller effluent concentrations of total N compared to complete-mix units [45].
271 In our study, N loss during curing appears to have been driven by volatilization of ammonia
272 (NH_4^+ to NH_3) or coupled mineralization-volatilization (organic N to NH_4^+ to NH_3) (Figure 1b
273 and 1c). The latter is supported by the fact that the total N reduction exceeds the inorganic N
274 measured in the initial fresh solid digestate for some samples. We observed traceable NO_3-N in

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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.

3.2. 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 (Figure 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) (Figure 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 amount of slow-release P (as defined here) may facilitate more efficient recycling of P from digestates to plants. Further experimentation is needed to test this hypothesis.

For cured solid digestate materials, total P ranged widely from 4.9-13.7 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

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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 (Figure 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 should 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 plant available in solid digestate materials over time.

3.3.Other nutrients

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

3.4. Plate competition assay

Growth of *R. solani* was reduced in cultures containing raw coarse solid digestate compared to corresponding reference (autoclaved) cultures for all materials tested (Figure 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 (Figure 2). This finding is supported by other studies that suggest more mature composts are more suppressive

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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].

4. 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. Nutrients contained in these digestate materials can be expected to largely become bioavailable 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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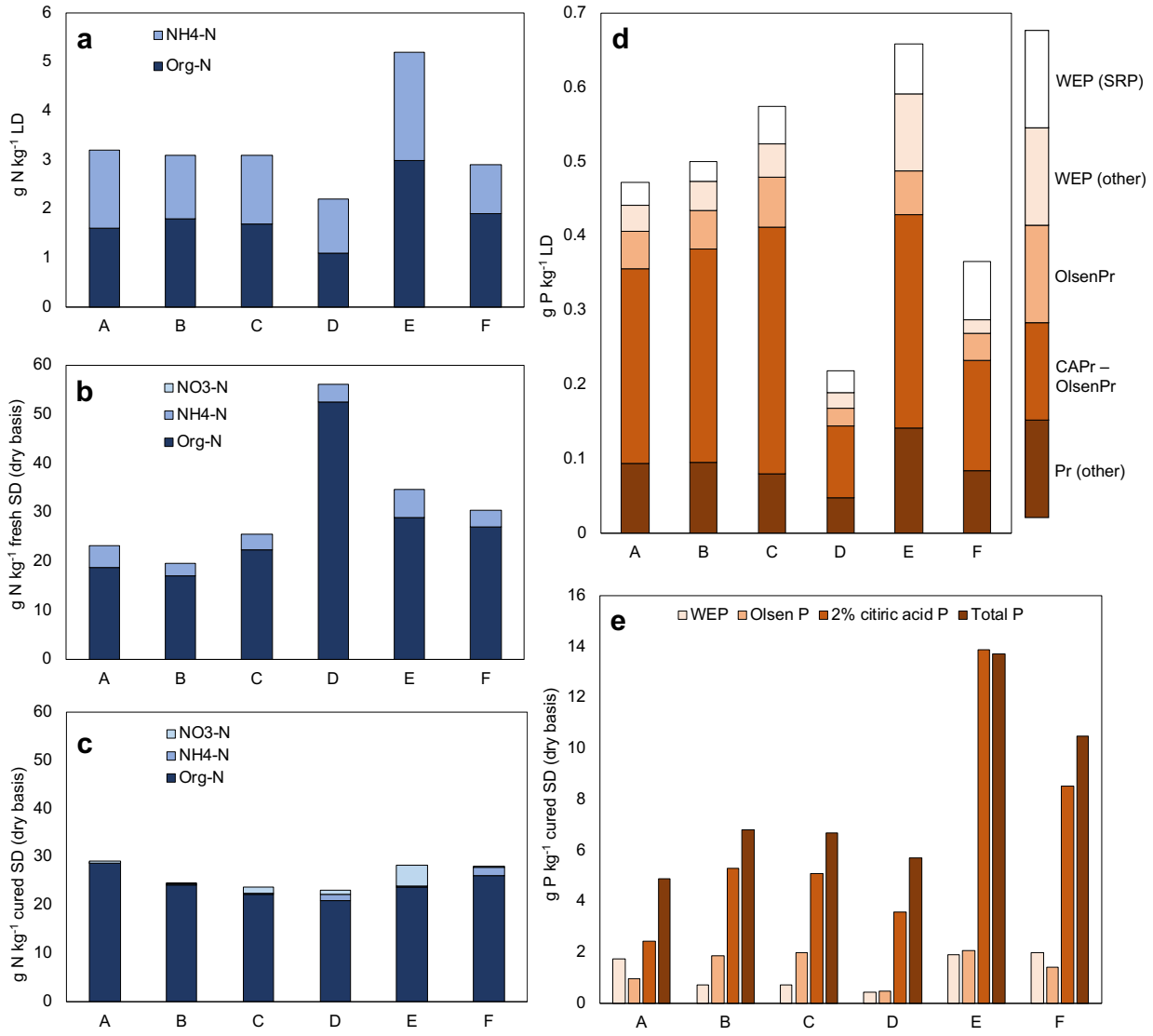

Figure 1. Nitrogen (a-c) and phosphorus (d-e) composition of liquid digestates (LD) and solid digestates (SD). Total N, NO_3-N, NH_4-N, organic N, and Total P for cured SD were initially reported in [18] for Digesters A and E only. WEP = water-extractable P. CAP = 2% citric acid extractable P. Pr in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

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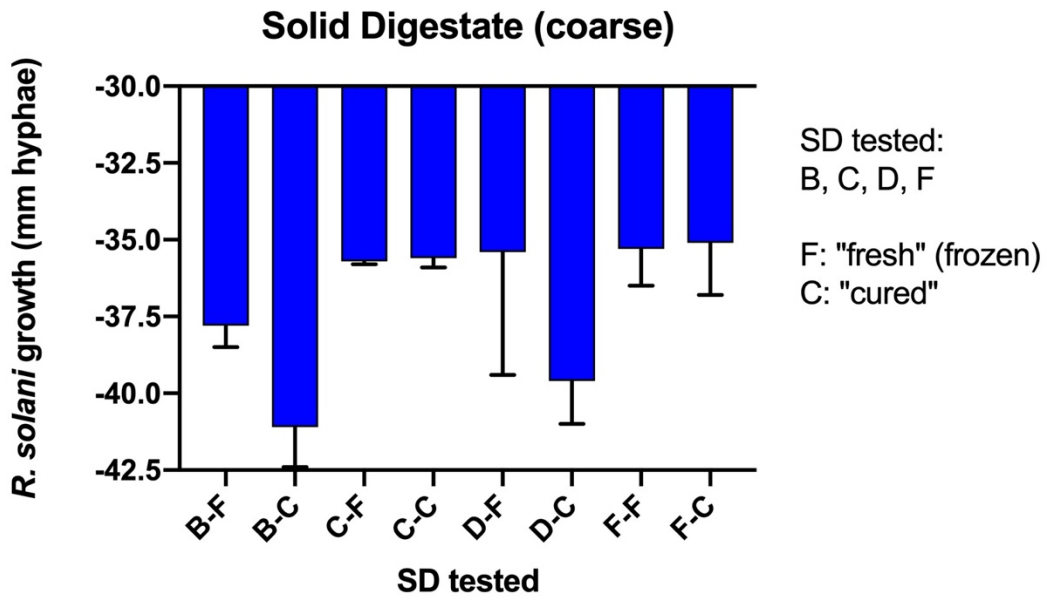

485

486 **Figure 2.** Plate competition assay measuring hyphal growth of *Rhizoctonia solani* on solid
487 digestate (SD) water extract agar from farms B, C, D, & F (fresh and cured SD). Illustrated are
488 means ± 1 standard error of the change from autoclaved control. Both controls and treatment
489 comparisons were inoculated with virulent *Rhizoctonia solani*.

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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*	% 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

* "food waste" includes source separated organics, dairy process waste, brewery waste, and whey waste water

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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

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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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Table 4. Nutrient composition of solid digestates (SD). Units are on a dry matter basis.

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

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SUPPLEMENTARY MATERIALS

Table S1. Digestates from cow manure and food waste feedstocks with parameters reported in literature. DS = Digester Scale: F = Full-scale biogas plant, L = Laboratory, pilot, or sub-commercial scale; For temperature, M = Mesophilic, T = Thermophilic; For form, D = Digestate (not separated) , Lq = Liquid fraction, S = Solid fraction; TS = Total Solids, VS = Volatile Solids; OFMSW = organic fraction of municipal solid waste, NS = Not specified; Total N as TKN unless specified otherwise.

Study	Feedstock	DS	Temp	Phase	pH	TS	VS	Total C	Total N	NH_4-N	Org-N	P
						g DM kg^{-1} FW	---------- g kg^{-1} dry matter ----------					
Albuquerque et al. (2012)	cattle slurry + 4% glycerine	L	M	D	5.6	-	-	465†	50*	26	-	13
	cattle slurry + 6% glycerine	L	M	D	7.3	-	-	587†	32*	12	-	5
	cattle slurry + 6% glycerine	L	M	D	6.4	-	-	472†	34*	23	-	6
	cattle slurry + 5% orange peel residues	L	M	D	7.9	-	-	385†	57*	33	-	8
	cattle slurry + 10% orange peel residues	L	M	D	7.9	-	-	330†	85*	51	-	11
Brod et al. (2015a; 2015b)	source-separated household waste	F	NS	Lq	7.0	24	646	412	95	-	25	12
				S	7.7	250	662	400	56	-	49	15
Coehlo et al. (2018)	food waste (dairy industry)	F	M	D	8.5	28	642	374†	165	-	-	12
	food waste (farm and food)	F	M	D	8.1	33	538	313†	75	-	-	33
	food waste, garden waste	F	M	D	8.2	36	475	232†	104	-	-	21
	whole cattle slurry	F	M	D	7.9	17	628	358†	101	-	-	10
	whole cattle slurry	F	M	D	8.3	48	721	419†	66	-	-	8
	food waste (kitchen), garden waste	F	M	D	8.1	49	707	411†	84	-	-	12

†Total Organic Carbon, *Total N determined by dry combustion with elemental analyzer

Table S1 continued. Digestates from cow manure and food waste feedstocks with parameters reported in literature. DS = Digester Scale: F = Full-scale biogas plant, L = Laboratory, pilot, or sub-commercial scale; For temperature, M = Mesophilic, T = Thermophilic; For form, D = Digestate (not separated) , Lq = Liquid fraction, S = Solid fraction; TS = Total Solids, VS = Volatile Solids; OFMSW = organic fraction of municipal solid waste, NS = Not specified; Total N as TKN unless specified otherwise.

Study	Feedstock	DS	Temp	Phase	pH	TS	VS	Total C	Total N	NH_4-N	Org-N	P
						g DM kg^{-1} FW	---------- g kg^{-1} dry matter ----------					
Haraldsen et al. (2011)	source-separated household waste	F	NS	D	8.0	15	-	-	152	104	48	16
Kirchmann & Witter (1992)	cattle slurry	L	M	D	8.5	19	-	500†	42	21	21	9
Lukehurst et al. (2010)	dairy cow slurry	NS	NS	D	7.9	-	-	-	61*	40	-	-
Möller et al. (2008)	cattle slurry	L	M	D	7.8	92	638	355†	43	21	22	7
Pognani et al. (2009)	22% energetic crops, 33% cow manure slurry, 45% agro-industrial waste	F	T	D	8.7	35	753	414†	105*	71	33	11
	2% energetic crops, 22% cow manure slurry, 18% agro-industrial waste, 59% OFMSW: NS	F	T	D	8.3	36	684	377†	110*	68	42	12
Risberg et al. (2017)	100% cow manure	F	M	D	-	74	-	459	46*	30	16	-
	45% waste from food processing industries, 50% source-separated organic waste, 5% garden waste	F	T	D	-	22	-	364	209*	164	45	-

†Total Organic Carbon, *Total N determined by dry combustion with elemental analyzer

Table S1 continued. Digestates from cow manure and food waste feedstocks with parameters reported in literature. DS = Digester Scale: F = Full-scale biogas plant, L = Laboratory, pilot, or sub-commercial scale; For temperature, M = Mesophilic, T = Thermophilic; For form, D = Digestate (not separated) , Lq = Liquid fraction, S = Solid fraction; TS = Total Solids, VS = Volatile Solids; OFMSW = organic fraction of municipal solid waste, NS = Not specified; Total N as TKN unless specified otherwise.

Study	Feedstock	DS	Temp.	Phase	pH	TS[a]	VS	Total C	Total N	NH_4-N	Org-N	P
						g DM kg^{-1} FW	---------- g kg^{-1} dry matter ----------					
Risberg et al. (2017) continued	90% cow manure, 10% waste from food processing industries	F	T	D	-	43	-	393	81*	56	26	-
Tambone et al. (2017)	cow slurry + cow manure + energetic crops + molasses	F	NS	D	-	72	-	-	93	64	29	21
				Lq	-	45	-	-	119	86	33	24
				S	-	202	-	-	30	16	15	10
Tampio et al. (2016)	source-separated domestic food waste	L	M	D	8.0	68	737	395	128	66	62	-
	source-separated domestic food waste	L	M	D	7.6	79	935	329	99	22	77	-
	source-separated domestic food waste	L	M	D	8.3	20	181	342	236	196	40	-
	OFMSW: NS	F	T	D	8.3	32	278	320	140	99	40	-
Tampio et al. (2015)	source-separated food waste	L	M	D	8.0	67	677	386	116	60	55	20
	autoclaved source-separated food waste	L	M	D	7.7	79	898	415	93	28	80	16

[†]Total Organic Carbon, [*]Total N determined by dry combustion with elemental analyzer

Table S1 continued. Digestates from cow manure and food waste feedstocks with parameters reported in literature. DS = Digester Scale: F = Full-scale biogas plant, L = Laboratory, pilot, or sub-commercial scale; For temperature, M = Mesophilic, T = Thermophilic; For form, D = Digestate (not separated) , Lq = Liquid fraction, S = Solid fraction; TS = Total Solids, VS = Volatile Solids; OFMSW = organic fraction of municipal solid waste, NS = Not specified; Total N as TKN unless specified otherwise.

Author	Feedstock	DS	Temp.	Form	pH	TS[a]	VS	Total C	Total N	NH_4-N	Org-N	P
						g DM kg^{-1} FW	---------- g kg^{-1} dry matter ----------					
Teglia et al. (2011)	70% bovine manure + 7% rabbit manure + 3% garden wastes + 17% fruits and vegetables	F	T	D	-	240	688	363	20	6	14	8
	OFMSW: 15% kitchen wastes, 75% garden wastes, 10% paper and cardboard	F	T	D	-	425	386	200	13	4	9	2
	OFMSW: 60% biowastes, 20% green wastes, 20% residual MSW	F	T	D	-	457	741	347	14	4	10	9
Walsh et al. (2012)	cow slurry	F	M	D	8.6	52	-	274	22*	20	-	1
Zhang et al. (2012)	source-separated domestic food waste	L	M	S	-	15	826	-	55	24	31	11
				Lq	-	6	712	-	112	65	47	12
	OFMSW: NS	L	M	S	-	35	605	-	16	5	11	3
				Lq	-	7	499	-	48	22	26	5

[†]Total Organic Carbon, [*]Total N determined by dry combustion with elemental analyzer

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Table S2. Nutrients in liquid digestates (LD) and cured solid digestates (SD). Units for SD are on a dry matter basis.

Parameter	Digester						Mean ± standard deviation
	A	B	C	D	E	F	
Liquids							
Total N (g N kg^{-1} LD)	3.2	3.1	3.1	2.2	5.2	2.9	3.3 ± 1.0
NH_4-N (g N kg^{-1} LD)	1.6	1.3	1.4	1.1	2.2	1.0	1.4 ± 0.4
Organic-N (g N kg^{-1} LD)	1.6	1.8	1.7	1.1	3.0	1.9	1.9 ± 0.6
Total P (g P kg^{-1} LD)	0.47	0.50	0.57	0.22	0.66	0.37	0.47 ± 1.6
Water-extractable P (SRP) (g P kg^{-1} LD)	0.03	0.03	0.05	0.03	0.07	0.08	0.05 ± 0.02
Water-extractable P (other forms) (g P kg^{-1} LD)	0.03	0.04	0.04	0.02	0.10	0.02	0.04 ± 0.03
Olsen P of fine solids (g P kg^{-1} LD)	0.05	0.05	0.07	0.02	0.06	0.04	0.05 ± 0.02
[2% citric acid P – Olsen P] for fine solids (g P kg^{-1} LD)	0.26	0.29	0.33	0.10	0.29	0.15	0.24 ± 0.09
P in fine solids not extracted by 2% citric acid (g P kg^{-1} LD)	0.09	0.10	0.08	0.05	0.14	0.08	0.09 ± 0.03
[2% citric acid P in fine solids – Water-extractable P (all forms)] (g P kg^{-1} LD)	0.25	0.27	0.31	0.07	0.18	0.09	0.20 ± 0.10
Total Potassium (g K kg^{-1} LD)	2.3	2.0	2.7	0.7	2.1	1.5	1.9 ± 0.7
Total Calcium (g Ca kg^{-1} LD)	0.90	1.1	1.3	0.40	1.3	0.70	0.95 ± 0.36
Total Magnesium (g Mg kg^{-1} LD)	0.50	0.80	0.50	0.20	0.30	0.20	0.42 ± 0.23
Boron (g B kg^{-1} LD)	0.00	0.00	0.00	0.00	0.00	0.00	0.0 ± 0.0
Copper (g Cu kg^{-1} LD)	0.03	0.09	0.03	0.00	0.00	0.01	0.03 ± 0.03
Iron (g Fe kg^{-1} LD)	0.04	0.04	0.03	0.09	0.11	0.30	0.10 ± 0.10
Manganese (g Mn kg^{-1} LD)	0.01	0.02	0.01	0.00	0.01	0.01	0.01 ± 0.00
Sodium (g Na kg^{-1} LD)	0.82	1.5	1.4	0.68	1.8	0.46	1.1 ± 0.52
Zinc (g Zn kg^{-1} LD)	0.01	0.02	0.01	0.01	0.01	0.01	0.01 ± 0.00
Fresh solids (dry)							
Total N (g N kg^{-1} fresh SD)	23.2	19.6	25.6	56.2	34.7	30.4	31.6 ± 13.2
NH_4-N (g N kg^{-1} fresh SD)	4.4	2.6	3.3	3.7	5.8	3.2	3.8 ± 1.1
NO_3-N (g N kg^{-1} fresh SD)	0.0	0.0	0.0	0.0	0.0	0.0	0.0 ± 0.0
Organic-N (g N kg^{-1} fresh SD)	18.8	17.0	22.3	52.5	29.0	27.1	27.8 ± 13.0
Cured solids (dry)							
Total N (g N kg^{-1} cured SD)	29.2	24.4	23.8	23.0	28.3	28.0	26.1 ± 2.7
NH_4-N (g N kg^{-1} cured SD)	0.2	0.2	0.1	1.2	0.1	1.9	0.6 ± 0.8
NO_3-N (g N kg^{-1} cured SD)	0.4	0.0	1.5	0.8	4.4	0.1	1.2 ± 1.7
Organic-N (g N kg^{-1} cured SD)	28.6	24.2	22.3	21.0	23.7	26.0	24.3 ± 2.7

Table S2 continued. Nutrients in liquid digestates (LD) and cured solid digestates (SD). Units for SD are on a dry matter basis.

Parameter	Digester						Mean ± standard deviation
	A	B	C	D	E	F	
Cured solids (dry)							
Total P (g P kg^{-1} cured SD)	4.9	6.8	6.7	5.7	13.7	10.5	8.1 ± 3.4
Water-extractable P (g P kg^{-1} cured SD)	1.7	0.7	0.7	0.5	1.9	2.0	1.3 ± 0.7
Olsen P (g P kg^{-1} cured SD)	1.0	1.9	2.0	0.5	2.1	1.4	1.5 ± 0.6
2% citric acid P (g P kg^{-1} cured SD)	2.4	5.3	5.1	3.6	13.9	8.5	6.5 ± 4.2
[2% citric acid P – water-extractable P] (g P kg^{-1} cured SD)	0.7	4.6	4.4	3.1	12	6.5	5.2 ± 3.8
Total Potassium (g K kg^{-1} cured SD)	0.01	0.01	0.01	0.00	0.01	0.01	0.10 ± 0.00
Sodium (g Na kg^{-1} cured SD)	0.04	0.02	0.03	0.01	0.03	0.04	0.30 ± 0.01
Total Magnesium (g Mg kg^{-1} cured SD)	0.02	0.00	0.00	0.00	0.00	0.00	0.00 ± 0.01
Boron (g B kg^{-1} cured SD)	0.41	1.20	0.49	0.05	0.09	0.09	0.39 ± 0.44
Copper (g Cu kg^{-1} cured SD)	0.69	0.59	0.56	1.86	2.24	8.88	2.5 ± 3.2
Iron (g Fe kg^{-1} cured SD)	0.01	0.01	0.01	0.00	0.01	0.01	0.01 ± 0.00
Manganese (g Mn kg^{-1} cured SD)	0.12	0.24	0.10	0.06	0.18	0.14	0.14 ± 0.06
Sodium (g Na kg^{-1} cured SD)	0.00	0.00	0.00	0.00	0.00	0.00	0.00 ± 0.00
Zinc (g Zn kg^{-1} cured SD)	0.14	0.20	0.17	0.11	0.13	0.12	0.14 ± 0.03