Aquacultural Engineering 115 (2026) 102778

Contents lists available at ScienceDirect

Aquacultural Engineering

journal homepage: www.elsevier.com/locate/aque

Co-composting aquaculture sludge at full-scale: Two case studies evaluating process performance and compost quality

Christine Lepine [*], Abhinav Choudhury, Kaid Ryland, Jacob Bell, Christopher Good

The Conservation Fund Freshwater Institute, 1098 Turner Road, Shepherdstown, WV 25443, USA

ARTICLE INFO

Keywords:
Aquaculture solid waste
Fish mortalities
Recirculating aquaculture systems (RAS)
Spent mushroom compost
Waste characterization
Waste valorization

ABSTRACT

Two consecutive case studies assessed the feasibility of composting dewatered sludge (DS; fecal matter and uneaten feed) obtained from recirculating aquaculture systems. Utilizing a commercially available rotary drum composter (3.15 m^3 working volume; 14-d retention time), DS was combined with wood flakes (WF) bulking agent and co-composted with either spent mushroom compost (SMC) in case study 1 or fish mortalities (FM) in case study 2. The case studies characterized feedstocks, evaluated potential recipes, and assessed process performance and finished product quality. In case study 1, co-composting DS with SMC (DS-SMC) reached thermophilic temperatures (average hottest-zone temperature of 58.8 ± 0.6 °C), thereby accelerating feedstock breakdown. Compost was considered stable and mature post-drum, as indicated by a low CO_2 respiration rate of 0.2 ± 0.0 mg CO_2-C/g OM/day, with a final C:N ratio of 19 ± 2 after a 6-month post-drum curing period. In case study 2, co-composting DS with FM (DS-FM) resulted in low hottest-zone temperatures (averaging 51.9 ± 1.0 °C), likely due to the heterogeneous nature of the combined feedstocks and increased drum rotations to minimize ammonia volatilization. High ammonium concentrations [571 ppm or 0.06%; 10% of total nitrogen (TN)] in the post-drum samples indicated incomplete decomposition. Six months post-drum, ammonia accounted for 1% of TN, but the C:N ratio remained elevated (28 ± 4). Additional analyses from both studies highlighted low concentrations of heavy metals and human pathogens. These two case studies suggest that co-composting with additional substrates may be an effective strategy for stabilizing aquacultural biosolids.

1. Introduction

High demand for seafood products has led to the rapid expansion of global aquaculture and, subsequently, its intensification (FAO, 2024). As natural water resources become increasingly scarce, the water recycling capabilities of land-based recirculating aquaculture systems (RAS) offer a sustainable model for the industry. While intensification in RAS increases fish production per unit area, the highly engineered design also generates a concentrated effluent containing fecal matter and uneaten feed, which is often dewatered into a thickened sludge.

Sludge management is a recurring cost that limits this burgeoning industry. Disposal or treatment of the concentrated, thickened sludge can be cost-prohibitive, especially in areas with stringent discharge regulations (van Rijn, 2013). Although the volume of waste sludge varies with the type of fish and production system, it is rich in organic matter (OM) and nutrients due to the presence of proteins and fats (Choudhury et al., 2023; Nhut et al., 2019). By applying circular bioeconomy principles, OM and nutrients from sludge could be recovered to generate a valuable and high utility product.

Composting is one of the most economical, practical, and robust techniques for converting manure and biosolids into a stable product with high fertilizer potential (Qasim et al., 2018). This exothermic process occurs in an aerobic environment where microorganisms convert OM into carbon dioxide (CO_2) and mineralize organically bound nutrients. Moreover, the composting process can reach thermophilic temperatures, which are essential for destroying pathogens commonly present in biological waste, such as fecal matter (Bhatia et al., 2012; Campanati et al., 2022; Fournel et al., 2019). The end product is rich in humus, nitrogen (N), and phosphorus (P), generally has no odor, and may be free of pathogens (Ho et al., 2022). Extensive research has been conducted on composting terrestrial animal manure-based substrates, whereas studies on aquaculture wastes are limited.

Adler and Sikora (2005) first investigated composting RAS dewatered sludge (DS) in windrows. Their study found that heat losses limited sustained pile temperatures and biological activity, and that mesophilic composting required at least 63 days to stabilize the materials. In

* Corresponding author.
E-mail address: clepine@conservationfund.org (C. Lepine).

https://doi.org/10.1016/j.aquaeng.2026.102778
Received 17 April 2026; Received in revised form 1 July 2026; Accepted 2 July 2026
Available online 4 July 2026

general, static windrows, a traditional composting method, requires long retention times. However, faster decomposition rates can be achieved through in-vessel composting (Fournel et al., 2019). Vessel agitation, with or without forced aeration (via a blower or fan), enhances oxygen transport and improves access to biodegradable matter. Thermophilic conditions can be achieved more rapidly, thus producing compost with more consistent quality (Hazarika and Khwairakpam, 2018; Stelmachowski et al., 2003). Automation and precision control of the in-vessel composting process help maintain adequate moisture levels and thermophilic conditions. Disadvantages include high capital cost, operator training and expertise, and access to power (Michel et al., 2022). Recent studies on the in-vessel composting of dried RAS sludge at the lab scale have investigated changes in drum rotation frequency to manage emissions and the addition of hydrochar to improve moisture retention (Liu et al., 2026; Zhang et al., 2026).

As a single waste stream, without a drying stage, RAS DS may be challenging to compost due to its high moisture content (MC) and low carbon:nitrogen (C:N) ratio (Lv et al., 2026). For an optimized composting process, the starting material should have a moisture content (MC) between 40–60% and a C:N ratio of 20:1–35:1 (Ekinci et al., 2020; Ho et al., 2022; Vázquez et al., 2015). However, these ranges may be wider, depending on the physical structure and particle sizes of the substrates (Vázquez et al., 2015). Aquaculture DS has MC levels similar to those of sewage sludge or municipal biosolids and thus requires dry bulking agents. A bulking agent is often used with the primary waste substrate (or substrates during co-composting) to absorb excess moisture, increase porosity to enhance aeration, and stabilize product quality (Toledo et al., 2019). Commonly used materials include wood chips, straw, or sawdust, which may also provide the carbon necessary to balance the C:N ratio for efficient breakdown of the organic material (Meng et al., 2017). However, the mixture of the bulking agent and DS may not maintain these parameters within optimal ranges. In such cases, additional organic substrates can be introduced to improve the composting recipe and overall efficiency through co-composting (Lv et al., 2026).

Co-composting the primary substrate (e.g., DS) with one or more waste substrates can also enhance the composting process by mitigating inhibitory conditions, improving compost quality by balancing nutrient ratios, and valorizing these materials simultaneously (Meng et al., 2017; Wu et al., 2010). Strategically selected co-substrates may also alleviate phytotoxic concerns by reducing potential heavy metal concentrations. Pérez-San Martín et al. (2025) co-composted thermally dried RAS DS (93% DM) with wood chips and perennial ryegrass in 200 L rotary bins and reported improved germination rates with co-composted dried RAS sludge compared to dry sludge alone; however, high zinc (Zn) concentrations limited the land application of their finished products.

Potential co-composting substrates could include spent mushroom compost (SMC), also known as mushroom soil, a byproduct of the mushroom production process that comprises leftover growing substrate (Fidanza et al., 2010). Past evaluations of SMC as a co-composting substrate for complex wastes have demonstrated its beneficial effects, due to enzymes such as protease, laccase, cellulase, and hemicellulase, which can rapidly break down recalcitrant and N-rich OM (Ko et al., 2005). Further benefits of SMC as a co-composting substrate include reduced compaction potential of the starting mixed material, thereby minimizing the formation of anaerobic zones (Zhang and Sun, 2014).

Fish mortalities (FM), which are occasionally generated during planned culling events on an RAS farm, may also serve as a sustainable, readily available co-composting substrate. Composting of fish mortalities, fish offal, and fish silage is well documented throughout the literature. Fish waste and byproducts are known to accelerate the thermophilic phase of decomposition by encouraging microbial activity and, subsequently, heat production (Liao et al., 1997). Additionally, FM contains high concentrations of soluble N, which have been shown to provide significant agricultural benefits for improving crop yields (Illera-Vives et al., 2015; Illera-Vives et al., 2017; Radziemska and Mazur, 2015). While DS requires a dry carbon-rich bulking agent to manage its high MC, adding FM as a co-composting substrate could be beneficial due to its complementary low C:N ratio and comparatively lower MC than DS.

In two consecutive case studies, SMC and FM were evaluated individually as co-composting substrates for RAS DS mixed with wood flakes (WF), to assess their impact on the composting process and the resulting compost quality. Study 1 evaluated RAS DS + WF + SMC (referred to as DS-SMC) and Study 2 evaluated RAS DS + WF + FM (referred to as DS-FM). These studies address a critical knowledge gap in sustainable RAS waste management by evaluating practical, farmer-friendly approaches to treating and valorizing aquaculture waste residues. To the best of our knowledge, this research also represents the first comprehensive commercial-scale assessment of in-vessel co-composting of RAS DS. Further, by characterizing feedstock characteristics, operating parameters, and the practical challenges of composting DS at a commercial scale, this work provides a foundation for the adoption and optimization of in-vessel composting within the aquaculture industry.

2. Materials and methods

2.1. Experimental setup and feedstocks

Two in-vessel compost case studies were conducted at an aquacultural research institute in a partially temperature-conditioned greenhouse (The Conservation Fund Freshwater Institute; Shepherdstown, WV, USA). A programmable plug-flow type rotary drum composter (2.95 m long, 1.5 m diameter, and 3.15 m^3 usable volume) that allowed for rotation scheduling and real-time temperature monitoring was used in the studies (Brome, model 510; Quebec, Canada). Each composting study consisted of 10 loading events, with new batches added every 3–4 days, maintaining at least 30% headspace within the vessel. Study 1 loading was conducted from mid-July through mid-August 2023, with an additional six-month post-drum curing phase lasting until February 2024. Study 2 loading occurred from mid-October through mid-November 2023, with the additional 6-month post-drum curing phase lasting until May 2024.

The feedstocks in each study consisted of RAS DS combined with pre-bagged kiln-dried WF (i.e., low-moisture)(Southern States; Ranson, WV, USA), which served as a high C:N ratio carbon source and bulking agent. The DS was generated onsite during RAS culturing of Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*). Waste solids, comprised of fecal matter and uneaten feed, were captured and dewatered via a 60 μm microscreen drum filter and gravitational thickening settlers (GTS), respectively (Fig. 1). For this study, backwash from the microscreen drum filters was thickened in a GTS before use, as mechanical dewatering and gravity settling are the most commonly used processes for this purpose at North American RAS farms. From the GTS, DS was pumped using an air-operated diaphragm pump (Sandpiper SPB20 Beast, Heavy Duty Flap Valve; Mansfield, OH, USA).

For co-composting substrates, Study 1 included SMC, a regionally available product purchased from a local garden store (Sunny Meadows; Boonsboro, MD, USA). Study 2 utilized FM (Atlantic salmon) collected from a single onsite culling event and kept frozen until the day before loading. For each loading event, two to three whole fish (i.e., heads, bones, skin, flesh, viscera) totaling ~20 kg were thawed at room temperature for ~24 h, then roughly cut across the backbone into several smaller pieces by hand (~2–3 in. thick) before being fed into the mixing equipment. Once combined, the feedstock materials were mechanically blended for approximately 20 min at a mixing/weighing station (Jay-Lor 50–50; Ontario, Canada) before being conveyed into the composter drum (Patz 1040 C; Pound, WI, USA)(Fig. 1).

Drum rotation and continual loading facilitated horizontal plug-flow movement of the mixed feedstock to the outlet, with a theoretical retention time of 14 days based on loading volumes and rates. Aeration using the vessel's built-in blower substantially increased heat loss during

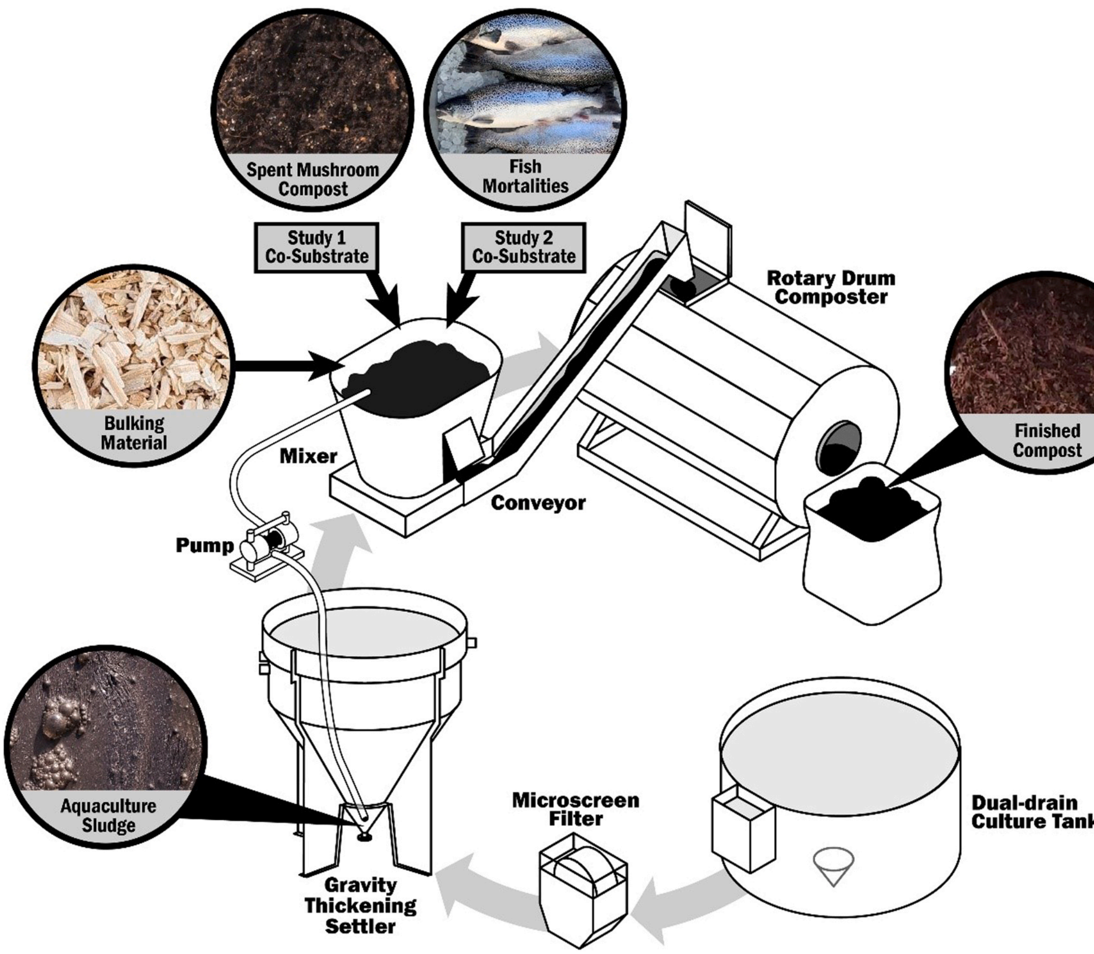

Fig. 1. Schematic and process flow diagram of the in-vessel composter setup.

pre-experiment trials; thus, on the advice of the compost manufacturer (personal communication), drum rotation was deemed sufficient to aerate the mixture. It should be noted that adequate process performance without forced aeration led to energy savings, as the only primary energy input occurred during drum rotation. As the system was not closed and air exchange was variable, continuous kinetic tracking of O_2 consumption and CO_2 evolution was not possible. The drum rotated one turn every five hours for DS-SMC (4–5 turns daily), with at least one additional turn during each loading and inlet-temperature reading event, thereby allowing passive oxygenation. For DS-FM, drum rotations were increased to once every four hours (6 turns daily) to increase passive aeration and reduce ammonia odor. Drum rotation frequency was continuously logged via the control panel (eWON eCatcher; Pittsburgh, PA, USA).

The resulting post-drum material was stored in ventilated, woven polypropylene bulk bags (Bag Supplies Canada Ltd., Ontario, Canada) inside the greenhouse for six months, allowing further examination and the determination of the compost's curing status.

2.2. Feedstock analyses

Individual feedstock materials (DS, WF, SMC, and FM), as well as those of the mixed materials (DS-SMC and DS-FM), were evaluated at a Seal of Testing Assurance (STA) Compost-Certified Laboratory (Agro-Lab; Harrington, DE, USA) following Test Methods for the Examination of Composting and Compost (TMECC) protocols (Thompson et al., 2001). The parameters tested included total solids (TS) or dry matter (DM) (TMECC 03.09-A), organic carbon (OC)(TMECC 04.01-A), total N (TN), organic N (TMECC 04.02-D), pH (TMECC 04.11-A), MC (TMECC 03.09-A), particle size distribution (PSD), heavy metals analysis & minerals (EPA method 3050B/6010 C & 7473), dissolved nutrients, and bulk density.

During the studies, some variability in the composition of the RAS DS was expected due to fluctuations in the fish populations and diets cultured at the research institute. Weekly grab samples were collected and analyzed onsite during each loading event to document these fluctuations (Appendix A1). Standard methods (APHA, 2012; Hach, 2021) were used for the analysis of pH (Accumet AB150; Devens, MA, USA), total ammonia N (TAN; Hach 8038), TN (Hach 10072), total phosphorus (TP; Hach 10210), dry matter and moisture (SM 22 2540 B), and organic matter and ash (SM 22 2540 E). Carbon content was estimated using the conversion factor from Adams et al. (1951), which was then used to calculate the C:N ratio.

2.3. Temperature

During the study, the inlet-side temperature, the hottest and most active zone within the drum, was spot-monitored five times per week using an Omega HH11C thermocouple (Norwalk, CT, USA) inserted to the same depth at grid points (0.76 ×0.61 m grid). Three readings were collected from each of three distinct zones within the inlet pile: (1) the front, which was closest to the inlet wall (Zone F; F1, F2, F3), (2) the middle of the pile (Zone M; M1, M2, M3), and (3) the back side, closest to the outlet side of the drum (Zone B; B1, B2, B3)(Fig. 2). The temperature of each zone was averaged (± SE) to account for hot spots.

Fig. 2. Temperature reading zones within the inlet compost pile.

2.4. Compost analyses

To track compost quality and process performance, pooled inlet and outlet samples (DS-SMC, $n = 10$; DS-FM, $n = 6$) were collected for further analysis at the STA Compost-Certified Laboratory (AgroLab, Harrington, DE, USA) in accordance with TMECC protocols. Analyses included microbial pathogens, metals, physical contaminants, pH, OM content, maturity, stability, conductivity, nutrient composition, and PSD. Additionally, the lab characterized compost maturity through bioassays of seed emergence (i.e., germination rate) and relative seedling vigor (i.e., seedling size, growth rate, and overall health).

Intermittent (2-month intervals) Solvita® maturity testing using kits (Solvita; Woods End Laboratories, Augusta, ME, USA) was conducted during the 6-month post-drum-curing period to help researchers determine when the compost was mature. The Solvita color values were also measured with the Solvita® digital color reader to ensure highly accurate readings. The 6-month-cured samples were again sampled for a final STA, nutrient composition, and PSD analysis.

2.5. Calculations

Mass balance calculations were conducted to determine mass loss, evaporative water loss, and losses of volatile solids, carbon, and N after the composting process. The conservation-of-ash-mass methodology, which assumes that the mass of fixed solids in the compost remains constant, was used to estimate the final wet mass of the compost DS-SMC (El Janati et al., 2023; Sommer and Dahl, 1999). Using this approach assumes that the compost mixture is relatively homogeneous, aided by the uniform distribution of SMC particles during mixing and composting. The average masses of the mixed material entering the composter and the compost product samples from all the batches in the study were used in the mass balance calculations. However, because DS-FM was highly heterogeneous due to discrete FM chunks, this approach could not be applied to the second case study. The final mass was estimated using the formula:

$$M_f = \frac{(M_i \ * \ A_i)}{A_f} \tag{1}$$

where M_f is the final mass of the composted product, M_i is the initial mass of the mixed material, A_f is the final percent ash in the compost, and A_i is the initial ash percent in the mixed material. The final mass was then used to calculate the evaporative moisture loss, total carbon and N loss, and volatile solids destruction.

Evaporative moisture loss was determined by using the formula:

$$ML = (M_i \ * \ MC_i) - (M_f \ * \ MC_f) \tag{2}$$

where ML is the mass of evaporative water loss, MC_i is the moisture content of the mixed material, and MC_f is the final moisture content of the compost.

Total N loss, volatile solids destruction, and organic carbon loss were also determined using the same approach:

$$TNL = (M_i \ * \ TN_i) - (M_f \ * \ TN_f) \tag{3}$$

$$VSL = (M_i \ * \ VS_i) - (M_f \ * \ VS_f) \tag{4}$$

$$TCL = (M_i \ * \ OC_i) - (M_f \ * \ OC_f) \tag{5}$$

where TNL is the mass of total N lost, VSL is the loss in volatile solids, and TCL is the loss in organic carbon during the composting process, TN_i, VS_i, and OC_i are the initial percent TN, VS, and organic C, respectively, in the mixed material, and TN_f, VS_f, and OC_f are the final percent TN, VS, and organic C, respectively, in the post-drum compost.

Additionally, the average fill fraction of the composter (to ensure it was not overloaded, thereby allowing for passive oxygenation) was calculated using the formula:

$$F = \frac{\left(\frac{M_i}{BD_i} \ * \ 4\right)}{V_c} \ * \ 100 \tag{6}$$

where F is the fill fraction, BD_i is the initial bulk density, and V_c is the composter volume (3.15 m^3). Based on the feeding schedule and the 14-day retention time during the study period, it was estimated that four batches of mixed feedstock material occupied the composter at any given time.

Free air space (FAS) to determine the adequacy of passive aeration of the starting mixed material inside the composter was calculated using an empirical relationship with BD_i (Agnew and Leonard, 2003).

$$FAS = 100 - (0.09 \ * \ BD_i) \tag{7}$$

3. Results and discussion

3.1. Feedstock characterization

Feedstock physicochemical characteristics (Table 1) and optimal parameters for MC (40–65%) and C:N ratio of 20:1–35:1 were used to develop the initial compost recipes (i.e., ideal theoretical loading volumes) for each study. A lower optimal theoretical C:N ratio was decided for Study 2, as rapid composting of fish mortalities can also occur between 10:1 and 20:1, since only the surface-available N is initially accessible to microorganisms (Timmons and Vinci, 2022). In general, a broader starting C:N ratio range of 15:1–35:1 is often considered acceptable for composting animal mortalities such as pigs, cows, and chickens (Matiz-Villamil et al., 2021; Morse et al., 2001).

Physicochemical analysis of the mixed materials (DS-SMC and DS-FM) pre-loading provided insight into the loading concentrations (Table 1). Additionally, recipe development also considered pH, with pre-loaded mixed material falling within the recommended range of 6.7–9.0 required for supporting microorganisms suited for composting for both studies (Fournel et al., 2019)(Table 1).

3.1.1. Study 1: DS + SMC loading and composition

Theoretical recipe calculations, based on the physicochemical characteristics of the individual materials, estimated that 30, 20, and 50% by mass of WF, SMC, and DS, respectively, would yield a mixed feedstock with an MC of 58%. Actual batches averaged 185 ± 3 kg per load, with WF, SMC, and DS contributing 45 ± 2, 38 ± 1, and 102 ± 2 kg, or approximately 24, 21, and 55% of each batch's mass, respectively. Using the actual loading ratios, the theoretical composition estimated that each batch had an MC of approximately 63% and a C:N ratio of 27.

The analyzed composition demonstrated a slightly higher MC of 66 ± 2% and a lower C:N ratio of 23 ± 2 (Table 1), placing MC just outside the optimum range. An MC > 65% can create anaerobic conditions that impede aerobic composting processes as pore spaces fill (Rynk et al.,

Table 1
Physicochemical characteristics [mean (± SE)]. Individual feedstock components: RAS dewatered sludge (DS), bulking agent (wood flakes, WF), and co-composting substrates of spent mushroom compost (SMC) or fish mortalities (FM). Mixed feedstocks pre-loading: of DS-SMC (Study 1) and DS-FM (Study 2). Results presented on a wet-weight basis.

Parameter	Unit	DS ($n = 7$)	WF ($n = 1$)	SMC ($n = 2$)	FM ($n = 4$)	DS-SMC ($n = 10$)	DS-FM ($n = 6$)
Organic N	% N	0.44 (0)	0.71	1.18 (0)	2.62 (0)	0.58 (0)	0.68 (0)
Ammonium	% N	0.06 (0)	0.03	0.06 (0)	0.02 (0)	0.01 (0)	0.01 (0)
Nitrate	% N	0.00 (0)	0.00	0.00 (0)	0.00 (0)	0.00 (0)	0.00 (0)
Total N	% N	0.50 (0)	0.74	1.24 (0)	2.64 (0)	0.63 (0)	0.69 (0)
Phosphorus	% P_2O_5	0.6 (0)	0.2	0.6 (0)	1.3 (0)	1.2 (0)	0.5 (0)
Potassium	% K_2O	0.0 (0)	0.5	1.4 (0)	0.4 (0)	0.3 (0)	0.0 (0)
Sulfur	% S	0.0 (0)	0.1	0.8 (0)	0.2 (0)	0.2 (0)	0.1 (0)
Calcium	% Ca	0.7 (0)	0.3	2.5 (0)	0.9 (1)	1.7 (0)	0.5 (0)
Magnesium	% Mg	0.0 (0)	0.1	0.4 (0)	0.0 (0)	0.1 (0)	0.0 (0)
Sodium	% Na	0.0 (0)	0.1	0.1 (0)	0.1 (0)	0.1 (0)	0.0 (0)
Zinc	ppm Zn	50 (7)	48	108 (7)	46 (2)	75 (7)	29 (5)
Iron	ppm Fe	131 (23)	159	1036 (192)	109 (34)	740 (87)	517 (232)
Manganese	ppm Mn	14 (2)	166	174 (12)	3 (1)	98 (9)	39 (6)
Copper	ppm Cu	4 (1)	34	94 (4)	3 (0)	24 (2)	4 (1)
Aluminum	ppm Al	38 (5)	68	726 (160)	1 (1)	283 (28)	66 (23)
Boron	ppm B	1 (0)	7	19 (1)	1 (0)	8 (1)	2 (0)
Soluble Salts	dS/m	6 (0)	0.2	6.4 (0)	4.0 (0)	2.3 (0)	0.7 (0)
pH	-	5.4 (0)	4.8	7.9 (1)	6.3 (0)	7.2 (0)	5.6 (0)
Moisture	%	91 (1)	6	55 (2)	57 (1)	66 (2)	63 (2)
Dry Matter	%	9 (1)	94	45 (2)	43 (1)	34 (2)	37 (2)
Ash	%	4 (0)	1	16 (0)	3 (1)	9 (1)	3 (1)
Organic Matter	%	4 (1)	93	30 (2)	40 (1)	25 (2)	34 (2)
Organic Carbon	%	2 (0)	54	17 (1)	23 (1)	14 (1)	20 (1)
Organic C:N	ratio	7 (1)	73	14 (0)	9 (0)	23 (2)	33 (5)
Bulk Density	kg/m^3	-	256	473 (40)	753 (0)	436 (31)	331 (34)

2022; Rynk, 1992). Although oxygen concentrations were not measured, the drum rotated one complete turn every five hours, with at least one additional turn during each loading and each inlet temperature reading, allowing for continuous passive oxygenation. The operational fill fraction during Study 1 was 54%, within the manufacturer's recommended range (< 70% of the total volume). Monitored temperatures indicated compost process performance (see 3.2.1 *Study 1: DS + SMC*) and helped guide operators to the appropriate number of drum rotations. The large particle size of the WF material (Appendix A2; 66% within 4.8–12.5 mm) also likely played a role in maintaining sufficient oxygen due to its high porosity. Furthermore, the calculated FAS from bulk density data in the starting mixture exceeded 60%, which is considered sufficient to maintain aerobic conditions with intermittent drum rotations in rotary-type composters (Jain et al., 2019). A recent study by Zhang et al. (2026) on rotary drum composting of dried RAS sludge also suggested that intermittent rotations may reduce greenhouse gas emissions while maintaining adequate oxygen levels for composting. In addition, continuous forced aeration reduced heat generation and caused fluctuations in process temperature in that study, similar to those observed in the pre-experimental trials of the current study.

3.1.2. Study 2: DS + FM loading and composition

Theoretical recipe calculations, based on the physicochemical characteristics of the individual materials, estimated that 33, 13, and 53% by mass of WF, FM, and DS, respectively, would yield a mixed feedstock with an MC of 60% and a C:N ratio of 20. Actual batches averaged 181 ± 4 kg per load, with WF, FM, and DS contributing 60 ± 3, 19 ± 1, and 102 ± 2 kg, or approximately 33, 11, and 56% of each batch's mass, respectively. Using the actual loading ratios, the theoretical composition derived from the physicochemical characteristics of the individual materials estimated that each batch had an MC of approximately 61% and a C:N ratio of 21. The sampled composition demonstrated a higher MC of 63 ± 2% and a higher, more variable C:N ratio of 33 ± 5 (Table 1). However, because the FM contributed a low % of the mass and was present in larger chunks, the sampled composition was likely not homogeneous and did not capture FM's contribution to the C:N ratio, and likely created localized zones of high N concentration.

Composting mortalities is challenging because it requires significant amounts of carbon, which limits the number of mortalities that can be composted (Bonhotal et al., 2022; USDA-NRCS, 2010). The high N content in mortalities also lowers the C:N ratio, which, at <20:1, increases the likelihood of N release via volatilization, as carbon is required to promote N-fixation (Hazarika and Khwairakpam, 2018; Magrí and Teira-Esmatges, 2015). During Study 2, operators intermittently detected a strong ammonia odor at both the inlet and outlet, indicating N release. Drum rotations were increased from once every five to once every six hours to improve aeration, which helped resolve the odor issues without substantially decreasing compost process performance (see 3.2.1 *Study 2: DS + FM*). The lower bulk density of the mixed material (331 ± 34 kg/m^3) resulted in a high average fill fraction of 69.4%, which was within the manufacturer's recommendations (<70%). Previous studies on similar commercially available rotary drum composters have suggested optimal fill fractions of 50–70% to maintain steady-state operation (Sharma et al., 2024).

3.1.3. Feedstock considerations for composting RAS wastes

Compost operators experienced challenges in achieving the calculated DS volumes in the starting mixture to optimize the initial C:N ratios. Sludge flow from the GTS was controlled using multiple valves at different locations, requiring two operators to work simultaneously. The combination of the mixing-scale lag time required to produce an accurate reading and the pump's tendency to pulse flow meant that the DS loading mass often exceeded the intended volume, as seen in both studies. Additionally, some minor variability in N concentrations in DS and MC was observed (Appendix A1). For farmers with inconsistent feeding rates or variable facility waste, it may be challenging to balance the compost recipe for each load optimally. From the practical standpoint of the farmer, this may be of less concern, as batches may average out over time.

Also of note was the large volume of dry, carbon-rich bulking agent required to balance the high MC of the DS. While this study did not include an economic analysis, using kiln-dried, bagged WF would likely be the farmers' most expensive option for carbon material (19.93 USD per cubic yard during these studies). Farmers could source lower-cost local carbon materials (e.g., recycled shredded pallets and untreated lumber) or collaborate with local farmers to obtain carbon waste residues (e.g., corn cobs), provided the materials were characterized for recipe development.

Incorporating an additional drying step for DS could eliminate the need for a low-MC, carbon-rich bulking agent and also reduce the overall amount of bulking agent required. Alternative DS thickening methods involve basins, geotextile bags, belt filters, and membrane reactors, which may be combined with coagulation and flocculation methods (van Rijn, 2013). However, additional pre-drying steps and equipment would also increase overall capital and operational costs, which may or may not offset the cost savings from higher MC carbon.

3.2. Composting process performance: temperature and nitrogen transformation

Temperature is a significant indicator of compost process performance, as it reflects microbial activity, which in turn determines decomposition rates, nutrient transformations, and pathogen reduction. During active composting, there are two distinct temperature phases: mesophilic (20–40 °C) and thermophilic (40–70 °C)(Ayilara et al., 2020). During the initial decomposition, mesophilic microorganisms rapidly break down soluble compounds (e.g., sugars and simple carbohydrates). As microbial respiration generates heat, pile temperatures rise into the thermophilic range, the most active phase of decomposition. The magnitude of the temperature increase during composting is controlled by microorganism enzymatic activity, which is directly influenced by the availability of readily biodegradable, energy-rich substrates (Meng et al., 2017). Microbial populations shift to favor thermophilic microorganisms, which break down organic matter (e.g., cellulose, hemicellulose, fats, and proteins). Temperatures of 55–65 °C are optimal for pathogen destruction (see also 3.7, Pathogen considerations), as higher temperatures (> 71 °C) may slow decomposition by reducing microbial diversity (Rynk, 1992). As easily degradable substrates are depleted, microbial respiration decreases, and pile temperatures gradually decline to ambient conditions. For these studies, the inlet side of the drum was spot monitored (Fig. 2). Temperatures could not be monitored as material moved through the drum, although an inline thermometer continuously logging near the outlet consistently demonstrated near-ambient temperatures for both studies (data not shown).

While complex in nature, N conversion during composting can also be a crucial indicator of its performance. Transformations include ammonification, ammonia assimilation, ammonia volatilization, nitrification, and denitrification, with the dominant reactions alternating based on environmental factors and the substrates in the mixture (Meng et al., 2017; Meng et al., 2018). While ammonia-N concentration was not continuously monitored in this study, the nitrification index (ratio of NH_4^+-N/NO_3^--N) can also serve as an indicator of process effectiveness and the maturity level of the composted product (Estrella-González et al., 2020; Meena et al., 2021). While nitrification is inhibited during the thermophilic phase of the process, nitrifiers become active once temperatures decrease to mesophilic levels (Aparna et al., 2008; Sánchez-Monedero et al., 2001).

3.2.1. Study 1: DS + SMC

Thermophilic temperatures for pathogen destruction were consistently maintained in the hottest zone during the co-composting of DS-SMC (Fig. 2a). Spot monitoring and frequent drum rotations ensured that pile temperatures remained within the optimum range (< 71 °C). The highest average temperatures were observed in zone B (i.e., closest to the outlet side of the drum; 58.8 ± 0.6 °C) and the lowest in zone F (i.e., closest to the inlet side wall; 45.4 ± 0.4 °C). This distribution is ideal for pathogen destruction, as the mixed material would likely pass through the composter's hottest zone on its way to the outlet.

The DS-SMC mixtures led to a rise in pile temperature after each loading event, occurring every 3–4 days (Fig. 3a). The presence of easily

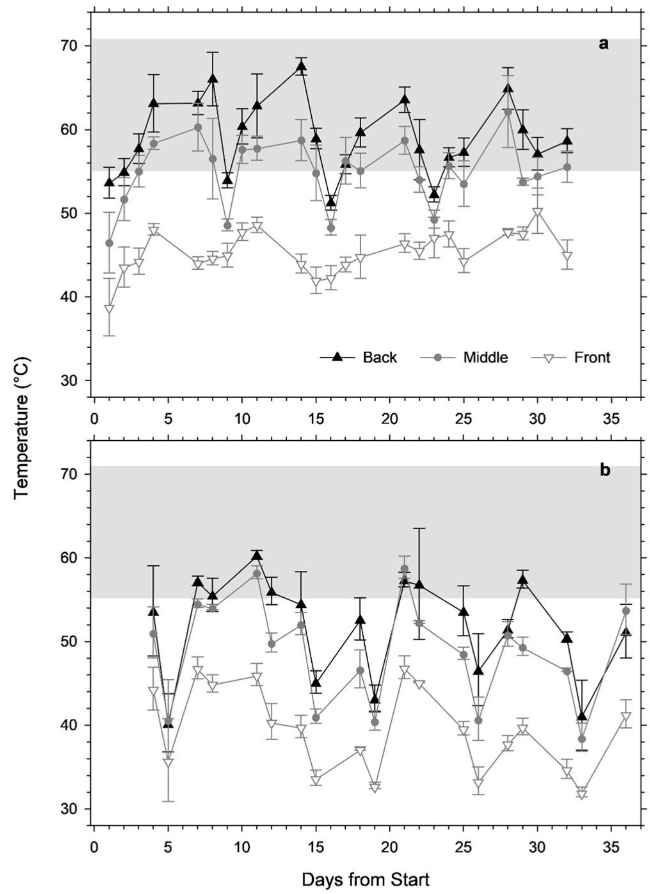

Fig. 3. Temperature (°C) spot monitoring of zones [back (B), middle (M), and front (F)] within inlet-side piles for in-vessel composting Study 1: DS-SMC (a) and Study 2: DS-FM (b). The grey-shaded area represents the desired temperature range for pathogen destruction (55 – 71 °C).

degradable OM in DS likely contributed to the rapid temperature increases. Sludge thickening in the GTS may have led to the hydrolysis of complex OM, thereby increasing its bioavailability to microorganisms (Choudhury et al., 2023; Choudhury et al., 2025). Moreover, the presence of enzymes in the SMC (laccase, protease, cellulase, and hemicellulase), along with its loose structure, likely facilitated greater oxygen availability, leading to higher microbial activity. While the cellulase and hemicellulase in SMC could also degrade the carbon in WF, the SMC macronutrients were more bioavailable, as they were already partially degraded during the mushroom production process (Zhang and Sun, 2014).

The nitrate-N (dry matter basis, Appendix A3) concentrations increased by a factor of 10 for DS-SMC (0.005–0.05%), while the ammonia-N (0.05%) concentrations remained the same at the outlet of the composter. Nitrification in DS-SMC most likely occurred once temperatures cooled to mesophilic levels near the outlet, resulting in a more favorable nitrification index of ~1 at the end of the 14-day process (Meng et al., 2018).

3.2.2. Study 2: DS + FM

The majority of all active composting temperature readings for DS-FM fell outside the optimal zone for pathogen destruction (Fig. 3b). The highest average maximum temperatures were observed in zone B (51.9 ± 1.0 °C), and the lowest in zone F (39.6 ± 0.7 °C). The recalcitrant nature of the carbon in WF and the limited mass of FM likely limited the temperature rise in DS-FM. As the carbon in WF was less bioavailable, FM's lower C:N ratio (9 ± 0) resulted in an overall energy-limited mixture for the microorganisms. It has been reported that only the surface-available macro- and micro-nutrients in animal mortalities are accessible to microorganisms during composting, thereby slowing the microbial breakdown process (Timmons and Vinci, 2022). Additionally, substrates with low C:N ratios may exhibit higher N conversion than carbon (Morisaki et al., 1989).

The ammonium concentration (dry matter basis; Appendix A3) increased dramatically from 0.02% to 0.15%, indicating that the breakdown process was not yet complete. High ammonia-N concentrations also promote N volatilization, further evidenced by the strong ammonia odor during the composting of DS-FM (Zhang and Sun, 2014). In some batches, smaller FM chunks were observed at the outlet, indicating incomplete degradation within 14 days. Nitrate concentrations (dry matter basis; Appendix A3) increased from 0.00% to 0.03%, suggesting some level of nitrification had initiated by the time DS-FM attained near-ambient temperatures near the outlet. The average nitrification index for DS-FM was 4.9 after 14 days. Nitrification indices > 3 indicate an immature product, whereas mature composts typically range from 0.5 to 3 (Estrella-González et al., 2020; Meng et al., 2017).

3.3. Mass balance

3.3.1. Study 1:DS + SMC

For DS-SMC, the average mass of fixed solids in the mixed material was calculated to be 16.4 kg (9% of the 185 kg batch average load during the study period). Due to the plug-flow nature of the composting system, continuous tracking of the total change in substrate mass was not feasible. Using the conservation of ash mass principle, the average final mass of each batch after the 14-day retention period was calculated to be 164.5 kg, a 10.9% (20 kg) reduction. Interestingly, a significant fraction of that reduction was attributed to evaporative moisture loss, accounting for approximately 92% of the total mass reduced. Evaporative moisture losses exceeding 90% may be observed during composting of substrates with a high starting MC, accounting for the majority of the mass loss during the process (Chiumenti, 2015). Only 1.6 kg of OM was destroyed per batch out of 45.5 kg of OM in the mixed material. Even though DS accounted for 55% of the initial mass in each batch of mixed material, its OM content was only 4.1 kg per batch, contributing 9% OM to the mixed material. As the wood flakes are highly recalcitrant and the SMC was partially pre-digested, the OM consumed during the active phase was likely derived primarily from DS.

A similar approach was utilized to track the N losses during the process. The initial mass of N was calculated to be 1.22 kg per batch, which decreased to 1.07 kg at the end of the active composting phase, a loss of 12.6%. The low loss indicates a low rate of ammonia volatilization, most likely due to the limited amount of easily degradable N and the near-optimal C:N ratio in the starting mixture. The initial mass of carbon in DS-SMC was 26.4 kg per batch, and 0.9 kg was lost over the 14-day period, which is low (3.5%) relative to the total mass of carbon in the starting mixture. However, this low value highlights the limited availability of readily degradable carbon and the practical challenges posed by the dilute nature of DS, as a large fraction of the starting material does not break down during the process, resulting in a low mass and volume reduction.

The six-month curing period resulted in further breakdown of the recalcitrant OM in the post-drum DS-SMC. The estimated average mass of each batch at the end of this period was reduced by 62.8 kg to 101.7 kg, a further 38% reduction. The moisture loss during this period was calculated to be 49 kg (78% of the total mass loss). Overall, an estimated additional 40% of the initial MC was lost during the curing phase. During this phase, a significant amount of carbon was also degraded. While the rate of degradation slowed, an additional reduction of 8 kg (total 8.9 kg) of carbon was observed by the end of the six months, resulting in a total carbon loss of 34% relative to the starting pre-composted mixture.

An additional 9% loss of N was observed during this period, but an estimated 78.5% of the mixture's initial N content was conserved by the end of the study. While N loss data in full-scale composting vary widely in the literature (between 19–77%), the observed values in this study were expectedly on the lower end of the spectrum due to limited N bioavailability in the co-substrates (Chiumenti, 2015). The difference between the initial and final mass of P was 2.2%, well within the error margins, indicating that the ash conservation principle used in the mass balance calculations was applicable in this study.

3.3.2. Study 2: DS + FM

As previously noted, the highly heterogeneous nature of DS-FM made it infeasible to apply this approach for mass balance calculations because the unmacerated FM chunks formed pockets of locally concentrated, nutrient- and ash-rich materials. It was challenging to obtain representative, homogeneous samples of the mixed material and the finished compost, which created a significant engineering limitation for modeling the composting of DS-FM at this scale.

3.4. Compost nutrient characterization

The nutrient concentrations in compost are lower than in fertilizers, although higher and more frequent compost applications allow for a cumulative effect on soils (Stehouwer et al., 2022). As a soil amendment, compost's value comes from improved soil structure, increased water-holding capacity, increased beneficial microbial activity, and the slow release of nutrients over time.

The different forms of N can characterize compost and are important metrics for measuring compost quality. In mature compost, 90–99% of TN is typically organic N. Conservative estimates suggest that only 5–10% of organic N mineralizes and becomes bioavailable within the first year (Amlinger et al., 2003), providing sustained nutrient release over a shorter pulse than fertilizer. Ammonium is an inorganic form of N and is highly bioavailable, though not all plant species can assimilate ammonium; however, high concentrations are generally associated with fresh or immature compost, which can burn seedlings. As compost matures, ammonium may volatilize into gas or be converted by nitrifying bacteria into nitrate. Increasing nitrate concentrations over time indicate that the compost is becoming mature or biologically stable. Nitrate provides highly bioavailable N but also leaches easily into groundwater, so it should remain a small percentage of TN.

The C:N ratio is often used to predict the probability of organic N mineralization, but only when organic carbon is readily biodegradable. However, the carbon in the WF feedstock used in these studies was not highly bioavailable and did not decay rapidly or readily. A higher C:N ratio in finished compost is generally undesirable for agricultural applications due to N immobilization, but it can still be used as a mulch or for erosion control (Rynk et al., 2022).

3.4.1. Study 1: DS + SMC

DS-SMC concentrations of TN, P, and potassium (K) after the six-month curing process (0.94 ± 0% N, 2.1 ± 0% P_2O_5, and 0.4 ± 0% K_2O, respectively; Table 2) correspond to a nutrient ratio of roughly 3:6:1, indicating a P-rich compost. While composted manures and biosolids are known to contain higher amounts of P than other feedstocks, in this case, the contribution is also due to the similarly high concentration of P within the SMC feedstock (0.6 ± 0% P_2O_5; Table 1). The K content in aquaculture sludge is generally lower than that of N and P (Rafiee and Saad, 2005).

The TN in the DS-SMC was primarily organic N in both fresh and cured composts (~90 and 91% of TN, respectively; Table 2), indicating mature compost. Maturity was also observed, as indicated by low ammonium in the cured samples (0.04 ± 0% N) and stable nitrate concentrations that were similar between the fresh and cured samples (0.02 ± 0 and 0.04 ± 0% N, respectively).

A decline in the C:N ratio of DS-SMC was observed between the fresh and cured samples (24 ± 2 and 19 ± 2, respectively; Table 2), a typical characteristic of most composts that have undergone a curing phase. The

Table 2
Characteristics of post-drum fresh and six-month-cured compost [mean (± SE)] for sludge co-composted with spent mushroom compost (DS-SMC; *n = 10*) and fish mortalities (DS-FM; *n = 6*) — results presented on a wet weight basis.

Parameter	Unit	DS-SMC		DS-FM	
		Fresh	Cured	Fresh	Cured
Organic N	% N	0.59 (0)	0.86 (0)	0.51 (0)	0.89 (0)
Ammonium	% N	0.02 (0)	0.04 (0)	0.06 (0)	0.01 (0)
Nitrate	% N	0.02 (0)	0.04 (0)	0.01 (0)	0.05 (0)
Total N	% N	0.65 (0)	0.94 (0)	0.58 (0)	0.95 (0)
Phosphorus	% P_2O_5	1.0 (0)	2.1 (0)	0.6 (0)	0.8 (0)
Potassium	% K_2O	0.5 (0)	0.4 (0)	0.1 (0)	0.5 (0)
Sulfur	% S	0.2 (0)	0.3 (0)	0.1 (0)	0.3 (0)
Calcium	% Ca	1.5 (0)	2.8 (0)	0.9 (0)	0.9 (0)
Magnesium	% Mg	0.1 (0)	0.2 (0)	0.0 (0)	0.1 (0)
Sodium	% Na	0.1 (0)	0.1 (0)	0.0 (0)	0.0 (0)
Soluble Salts	dS/m	5.1 (0)	4.9 (0)	4.4 (0)	4.2 (0)
pH	-	6.9 (0)	7.1 (0)	7.6 (0)	6.4 (0)
Moisture	%	63 (0)	54 (2)	62 (2)	52 (4)
Dry Matter	%	37 (0)	46 (2)	38 (2)	48 (4)
Ash	%	10 (1)	16 (1)	4 (0)	6 (1)
Organic Matter	%	27 (1)	30 (2)	33 (2)	42 (3)
Organic Carbon	%	15 (1)	17 (1)	19 (1)	24 (2)
Organic C:N	ratio	24 (2)	19 (2)	35 (2)	28 (4)
Bulk Density	kg/m^3	357 (21)	293 (10)	278 (30)	219 (10)

low C:N ratio indicates it is suitable as a nutrient source for plants.

3.4.2. Study 2: DS + FM

DS-FM concentrations of TN, P, and K after the six-month curing process (0.95 ± 0% N, 0.8 ± 0% P_2O_5, and 0.5 ± 0% K_2O, respectively; Table 2) correspond to a nutrient ratio of approximately 2:2:1, indicating twice as much N and P as K, but more balanced than DS-SMC.

Bioavailable N in the form of ammonium in the fresh samples (0.06 ± 0% N) decreased by 83% in the six-month cured DS-FM samples (0.01 ± 0% N; Table 2). The nitrate concentration increased substantially in the six-month-cured DS-FM samples (0.05 ± 0%N, up from 0.01 ± 0% N, in the cured samples), which coincided with the decrease in ammonium-N concentration during the curing phase, indicating nitrification. The decrease in DS-FM pH from 7.6 ± 0 to 6.4 ± 0 (Table 2) at the end of the six-month curing phase is another indicator of nitrification, as hydrogen ions are released during the reaction (Bożym and Siemiątkowski, 2018). While the TN in the fresh and cured DS-FM was primarily organic N (~88% and ~94% of TN, respectively; Table 2), the lower percentage in the fresh compost further highlighted the need for a curing period.

The inlet DS-FM mixture had a high average C:N ratio (33 ± 5; Table 1), and the fresh samples had a similar average C:N ratio (35 ± 2; Table 2). It was challenging to analyze DS-FM's C:N ratio due to its heterogeneous nature resulting from the inclusion of discrete FM chunks that likely created localized zones of high N concentration, and subsequent ammonia volatilization. However, as the ammonia volatilization was not quantified, only observed by the odor and suggested by the high ammonium concentrations at the outlet, further studies are needed to validate this hypothesis. These results indicated limited degradation of the bulk material during the 14-day HRT, as corroborated by lower pile temperatures and smaller FM chunks observed at the outlet. Analysis of six-month-cured DS-FM samples showed an average C:N ratio of 28 ± 4, suggesting some degradation of the bulk material during the maturation phase. The high C:N ratio of the cured DS-FM suggests it may be more suitable for use as a compost mulch than as an agricultural soil amendment, as it may cause soil microorganisms to deplete bioavailable N from the soil.

3.5. Maturity and stability

Maturity and stability, or the degree of completeness and the state of OM decomposition during composting, are quantitatively assessed through multiple characteristics, yielding a qualitative determination. Maturity is related to the presence or absence of phytotoxic components, like free ammonia, organic acids, or water-soluble compounds that may inhibit/retard plant growth (Ponsá et al., 2009; Soriano-Disla et al., 2010). It can also be assessed by measuring the ammonia (NH_3) gas concentration in a contained sample and by calculating the nitrification index, with values of 0.5–3.0 generally indicating mature compost (Meng et al., 2017). Similarly, stability correlates with microbial activity, as measured by CO_2 release (Ponsá et al., 2009; Soriano-Disla et al., 2010).

Additionally, pH levels and soluble salt concentrations correlate with seedling emergence and vigor. Organic acids are released as fungi and bacteria assimilate OM, causing the pH to drop in the beginning stages of composting as the acids accumulate. The acidic environment further promotes the initial breakdown of cellulose and lignin, although the organic acids are eventually broken down during decomposition. The preferred range for seed germination and most agricultural applications is 6.0–7.5. The electrical conductivity (EC) of soluble salts (i.e., soluble ions) is often correlated with the fertility level of the compost product, as most plant nutrients are bioavailable as salts. High soluble salt concentrations can cause phytotoxicity, burning plant roots while interfering with nutrient and water transport (Bhatia et al., 2012; Hazarika and Khwairakpam, 2018). Compost generally ranges from 1 to 10 dS/m, though < 5 dS/m is preferred for most plants (Gondek et al., 2020).

3.5.1. Study 1: DS + SMC

After a 14-day retention period, DS-SMC demonstrated 100 ± 0% seed emergence and 89 ± 3% seedling vigor (i.e., mature to very mature), indicating complete composting had occurred. After a six-month cooling period, the compost composition was similar, with 99 ± 1% seed emergence (i.e., very mature) and 92 ± 1% seedling vigor (i.e., mature to very mature), indicating that no further benefit was gained from an additional curing phase. The pH and conductivity of soluble salts further demonstrated this. The pH remained relatively neutral (i.e., ideal for plant germination and growth) and stable between the post-drum and cooling periods (6.9 ± 0 and 7.1 ± 0, respectively; Table 2). Soluble salts conductivity was also comparable between periods and in the favorable range for plants (5.1 ± 0 and 4.9 ± 0 dS/m, respectively; Table 2). The respiration rates for both the post-drum and six-month-cured samples were stable at 0.2 mg CO_2-C/g OM/day, indicating a highly stable product.

These results were also supported by Solvita® testing results, which demonstrated the highest possible rating on the compost maturity index across post-drum fresh to six-month-cured samples (Bhatia et al., 2012; Kalamdhad and Kazmi, 2009; Kalamdhad et al., 2008). The ammonia concentrations in the Solvita® jar headspace for both the post-drum and 6-month post-drum DS-SMC samples were estimated to be < 10 ppm. The nitrification index of DS-SMC also corroborated the Solvita data; the index hovered around 1 for both the fresh post-drum and six-month-cured samples, indicating mature compost (Meng et al., 2017). Overall, full-scale in-vessel co-composting of DS with SMC produced mature compost substantially faster (14 days) compared to windrow composting of DS (between 63 and 167 days, depending on the carbon source)(Adler and Sikora, 2005) or the composting of dried RAS DS in rotary bins (120 days) (Pérez-San Martín et al., 2025). The latter study of dried RAS DS may have taken so long to reach maturity due to lowered biological activities, as the finished compost had an MC of only 5.5%.

3.5.2. Study 2: DS + FM

Compost DS-FM exhibited high seed emergence in post-drum fresh and six-month cured samples (100 ± 0% and 97 ± 3%, respectively). However, seedling vigor was initially low at 80 ± 2% (i.e., immature to mature) in the fresh compost samples and increased to 89 ± 3% (i.e., mature to very mature) after the six-month maturation phase. Interestingly, the pH decreased between the post-drum and cooling periods (7.6

± 0 and 6.4 ± 0, respectively; Table 2), a change that is linked to nitrification in compost (Sánchez-Monedero et al., 2001). For fresh and cured samples, soluble salt conductivity for DS-FM was comparable (4.4 ± 0 and 4.2 ± 0 dS/m, respectively; Table 2). The average respiration rate for the post-drum fresh DS-FM samples was 0.2 mg CO_2-C/g OM/day, suggesting that carbon degradation rates had decreased to levels similar to those observed in DS-SMC by the end of the 14-day active composting phase. The low seedling vigor observed in the fresh DS-FM samples during testing was likely due to the high ammonia concentrations.

Solvita® testing also demonstrated lower ratings on the compost maturity index for the fresh DS-FM. Average ammonia concentrations in the headspace of the Solvita® jar were estimated at > 7000 ppm (>10,000 ppm in the Week 1 samples) for the post-drum samples, corroborating the low seedling vigor results. The headspace ammonia concentrations decreased to < 10 ppm after two months for all samples, resulting in them testing as mature on the index. The fresh DS-FM compost benefited from the additional maturation phase, and the Solvita® results suggest that less than six months were needed to obtain a mature compost product. However, because the complete compost analysis was conducted only after six months, further studies may be necessary to corroborate the Solvita® results. The cured DS-FM had likely matured, as the nitrification index decreased to 0.2 after six months (from 4.9 after 14 days of retention time in the composter), another indication of nitrification during the maturation phase in addition to the pH decrease.

3.6. Metals

Trace metal concentrations in compost are often regulated due to their potential toxicity to plants and animals. Guidance on materials originating from feedstocks such as biosolids is federally regulated in the US for heavy metal concentrations of arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), mercury (Hg), nickel (Ni), selenium (Se), and Zn (US EPA, 1993). Certain metals, such as Cu and Zn, which are often added to aquaculture feeds to improve fish health, can accumulate in DS. At elevated concentrations, especially in dried DS, these metals can cause phytotoxicity, severely limiting their use as soil amendments (Brod et al., 2017; Choudhury et al., 2025; Pérez-San Martín et al., 2024; Pérez-San Martín et al., 2025). Composting or co-composting DS with a carbon source or additional substrates low in heavy metals may alleviate those challenges, as observed in this study.

The analysis of metals in DS-SMC and DS-FM (Table 3) showed only low concentrations across all measured parameters, none of which were considered phytotoxic, especially at the near-neutral pH of these composts. High quantities of metal elements, such as aluminum (Al), boron (B), manganese (Mn), molybdenum (Mo), Ni, and Se, are known to cause phytotoxic effects in plants (Vatansever et al., 2017), making their concentrations a crucial consideration for farmers. However, small quantities of metals Cu, iron (Fe), Mo, Ni, and Zn are needed for beneficial plant growth and development (Vatansever et al., 2017). Concentrations of heavy metals were also considerably below the maximum allowable concentrations set forth for STA Certified composts and EPA 40 CFR Part 503 – Standards for the Use or Disposal of Sewage Sludge (Table 3) (US EPA, 1993).

3.7. Pathogen considerations

An important factor to consider when composting RAS DS and FM is that the TMECC protocol testing is limited to human pathogens (*Salmonella* and fecal coliforms), which are not found in cold-blooded species such as finfish. All samples post-drum (fresh) and six-month(-cured) tested as non-detect for *Salmonella*, although its introduction is unlikely in indoor finfish aquaculture unless the source water or feed is contaminated (Porto et al., 2022). Fecal coliform screening was also performed on the six-month-cured samples for DS-FM (38 ± 5 MPN CFU/g on a dry basis; $n = 6$), demonstrating that the pathogen counts were substantially lower than the US EPA-specified limits for composted sewage sludge biosolids (US EPA, 1993).

Under EPA 40 CFR Part 503, a sewage-sludge biosolid is classified as Class A (i.e., the highest classification and subject to minimal restrictions on land application) when its pathogen count is below US EPA limits (US EPA, 1993). For in-vessel composting systems, the pathogen count is expected to be below the EPA standard limits (< 3 most probable number (MPN) of colony-forming units (CFU)/4 g of dry compost of *Salmonella*, and < 1000 MPN of CFU/g dry basis of fecal coliforms) when the temperature of the biosolids is maintained at 55°C or higher for at least three days. While this standard applies to sewage sludge (biosolids), the results of this study show that composted DS-SMC would meet Class A biosolid requirements for land application based on measured *Salmonella*/fecal coliform results.

As these waste substrates were obtained from a coldwater RAS facility, most endemic finfish pathogens were likely destroyed at the temperatures attained during composting. However, because this was not explicitly screened using the standard TMECC testing protocols, there is a risk of pathogen contamination of agricultural runoff to local watersheds after land application. Future studies should verify the

Table 3
Trace metals analysis [mean (± SE); mg/kg, dry weight] of compost generated after aquaculture sludge was co-composted with spent mushroom compost (DS-SMC) or fish mortalities (DS-FM; $n = 6$). Fresh compost samples were obtained post-drum, after a two-week retention time, and again in six months after maturation (cured samples). The maximum allowable concentrations in compost are based on STA Certified Compost parameters, as suggested by EPA 40 CFR Part 503 – Pollution Concentration Limits.

Parameter	Max. allowable*	DS-SMC		DS-FM	
(mg/kg)	(mg/kg)	Fresh	Cured	Fresh	Cured
Aluminum (Al)	-	778 (67)	853 (72)	265 (29)	218 (60)
Arsenic (As)	41	1.2 (0.4)	1.3 (0.2)	2.3 (0.6)	1.4 (0.5)
Boron (B)	-	19 (1)	15 (1)	8 (1)	6 (1)
Cadmium (Cd)	39	0.8 (0.3)	0.5 (0.0)	0.3 (0.0)	0.3 (0.1)
Chromium (Cr)	-	4.3 (0.3)	6.0 (0.5)	1.8 (0.2)	2.1 (0.6)
Copper (Cu)	1500	83.4 (11.2)	81.4 (7.4)	27.1 (4.1)	18.9 (3.5)
Iron (Fe)	-	2274 (238)	1805 (114)	757 (55)	417 (86)
Lead (Pb)	300	2.4 (1.0)	0.7 (0.3)	1.4 (0.3)	0.1 (0.1)
Manganese (Mn)	-	255 (13)	338 (15)	151 (22)	103 (18)
Mercury (Hg)	17	0.007 (0.003)	0.016 (0.002)	0.003 (0.001)	0.002 (0.000)
Molybdenum (Mo)	-	1.6 (0.3)	1.8 (0.2)	0.9 (0.2)	0.5 (0.2)
Nickel (Ni)	420	3.4 (0.4)	6.3 (1.3)	1.7 (0.1)	2.0 (0.3)
Selenium (Se)	100	0.6 (0.2)	0.5 (0.2)	0.7 (0.4)	0.7 (0.3)
Zinc (Zn)	2800	185 (17)	292 (15)	128 (22)	127 (45)

*Maximum EPA concentration expressed on a dry weight basis; Al, B, Cr, Fe, Mn, and Mo do not have EPA limits.

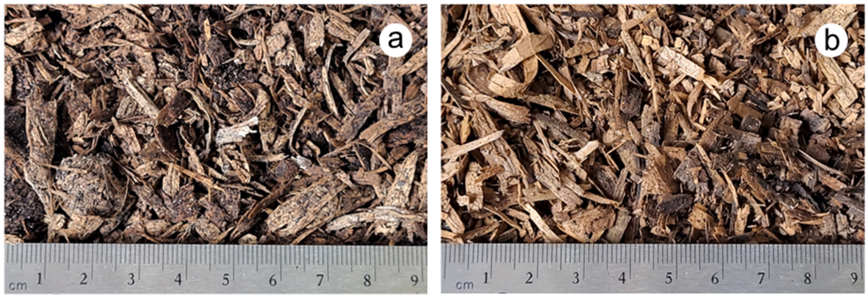

Fig. 4. Mulch-like compost product six-month post-drum from Case Study 1: DS-SMC (a) and Case Study 2: DS-FM (b).

destruction of relevant finfish pathogens in addition to human pathogens prior to land application to address site-specific biosecurity risks.

3.8. Compost application

The overall performance quality of a compost is variable and dependent on its intended function. In addition to product safety (e.g., pathogens, metals, and organic contaminants) and initial determinations of maturity and stability, the compost's nutrient concentrations, organic matter content, particle size, moisture content, bulk density, inorganic contaminants, and potential odors further assist in determining prospective applications (Stehouwer et al., 2022). Furthermore, soil amendment application is tailored to individual needs, as plant species vary in their requirements and limitations, and background soil characteristics are site-specific. Farmers can use the aforementioned compost performance quality characteristics and available first-year nutrient release data (Appendix A4) to determine whether the product will meet its intended use, identify the most appropriate application rate for the material, and, if required, obtain land-application permits.

Both DS-SMC and DS-FM (six-month-cured) exhibited high OM content (30–42%; Table 2), as expected given the characteristics of the feedstocks. Organic matter content is highly desirable, as agricultural soils tend to be OM-deficient (Magdoff, 2021). However, not all OC is plant-available, primarily due to the recalcitrant nature of wood-based materials. A quarter to a third of the feedstock in DS-SMC and DS-FM, respectively, was WF, which did not readily break down into a humus-like product. While particle sizes were slightly reduced after curing, DS-SMC (19.8% below 1 mm) and DS-FM (12.1% below 1 mm) (Appendix A2), the finished product resembled mulch more than humus (Fig. 4). However, 96 and 94% of finished DS-SMC and DS-FM's PSD, respectively was in the range (< 9.5 mm; Appendix A2) suggested by the US Composting Council's Consumer Compost Use Program for incorporation into soils (i.e., a soil amendment) for use with trees, shrubs, flowers, vegetables, and lawns (US Composting Council, 2020a; US Composting Council, 2020b; US Composting Council, 2020c).

Other considerations for compost application include aesthetics and utility. The MC of the finished product was relatively high in the fresh samples (63 ± 0% and 62 ± 2%, for DS-SMC and DS-FM, respectively; Table 2) but was reduced to a more preferred range after curing (54 ± 2% and 52 ± 4%, for DS-SMC and DS-FM, respectively; Table 2). The preferred MC for finished compost is generally 40 – 50% (Ozores-Hampton et al., 2022). Increased MC makes materials dense and clumpy, which may make application difficult. Neither of the cured composts (Fig. 4) appeared dense or clumpy, owing to the residual WF's low bulk density and high moisture absorption capacity. No artificial contaminants were introduced, so the end product of all batches contained < 0.1% human inerts and plastic film, with little to no visible inorganic contaminants (e.g., stones, rocks, sticks, or twigs). Furthermore, no odors were noted in any of the cured DS-SMC and DS-FM samples.

The characteristics of compost generated in both case studies demonstrate their theoretical value. Due to local regulations requiring extensive permitting, the generated compost could not be used for field application or agronomic performance testing, which would have demonstrated real-world effectiveness. Future studies should be incorporated to evaluate their potential use in practical agricultural and horticultural settings, substantiating product quality and value.

4. Conclusion

Compost was successfully generated through in-vessel co-composting of RAS DS with either SMC or FM. In the first study, the addition of SMC as a co-composting substrate resulted in thermophilic process temperatures (>55 °C), rapid decomposition, and a low ammonia concentration (177 ppm or 0.02%) at the end of the 14-day in-vessel retention period. Mass balance calculations indicated that only 10.9% of the mass in the starting mixture was lost during the active composting phase, with 92% attributed to evaporative moisture loss. In the second study, the DS-FM mixture resulted in temperatures below 55 °C and high ammonia concentrations post-drum (571 ppm or 0.06%), requiring at least 2 months of curing to attain stability and maturity. Carbon dioxide evolution rates for both DS-SMC and DS-FM post-drum were at or below 0.2 mg CO_2-C/g OM/day, indicating marked depletion of labile carbon in both case studies. Despite lower process temperatures during DS-FM composting, analyses indicated fecal coliforms and *Salmonella* were significantly below EPA standards for human pathogens. Co-composting with either SMC or FM substrate also helped limit the impacts of heavy metal accumulation in DS on the finished compost's agricultural use. While not strictly comparable, the poorer overall results for DS-FM suggest that further research is needed to develop optimal recipes to enhance the end-use and value of finished products from the combination of these two substrates. As seen in previous research on sewage sludge, SMC appears to be a more suitable and versatile co-composting substrate for DS, as it disperses evenly, adds volume, biodegradable carbon, and enzymes to the mixture, likely enhancing biological activity and leading to faster breakdown and better product quality. These demonstration case studies focused on proof of concept and considerations for farmers' ease of operation. While critical engineering data, process performance, pathogen destruction, heavy metal concentrations, and compost quality were included in the analysis, there were limitations and boundaries to these case studies (especially, DS-FM), including field application trials. Additionally, further economic analysis is needed to determine the most cost-effective methods for composting RAS DS and to weigh the potential resale value of compost against the costs of other disposal options.

CRediT authorship contribution statement

Abhinav Choudhury: Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kaid Ryland:** Writing – original draft, Project administration, Methodology, Investigation, Data curation. **Christine Lepine:** Writing –

review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christopher Good:** Writing – review & editing, Funding acquisition. **Jacob Bell:** Writing – original draft, Project administration, Methodology, Investigation, Data curation.

Funding

This work was supported by the United States Department of Agriculture – Agricultural Research Service agreement number 59–8082–0–001.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank Megan Murray and Sarah Rice for the water quality analysis and Scott Tsukuda, Shanen Cogan, and J.C. Stanley for project construction, plus operational and maintenance expertise. All authors listed have substantially contributed to this research according to the journal's standards for authorship qualification. Any trade, firm, or product name used is for descriptive purposes and does not imply endorsement. The authors declare no conflicts of interest. The Conservation Fund is an equal-opportunity employer.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aquaeng.2026.102778.

Data availability

Data will be made available on request.

References

Adams, R.C., Bennett, F.M., Dixon, J.K., Lough, R.C., Maclean, F.S., Martin, G.I., 1951. The utilization of organic wastes in NZ. N. Z. Eng. 6 (11), 396–424. 〈https://search.informit.org/doi/10.3316/informit.359233295091848〉.

Adler, P.R., Sikora, L.J., 2005. Mesophilic composting of arctic char manure. Compost. Sci. Util. 13, 34–42. https://doi.org/10.1080/1065657X.2005.10702215.

Agnew, J.M., Leonard, J.J., 2003. The physical properties of compost. Compost. Sci. Util. 11 (3), 238–264. https://doi.org/10.1080/1065657X.2003.10702132.

Amlinger, F., Götz, B., Dreher, P., Geszti, J., Weissteiner, C., 2003. Nitrogen in biowaste and yard waste compost: dynamics of mobilisation and availability—a review. Eur. J. Soil. Biol. 39, 107–116. https://doi.org/10.1016/S1164-5563(03)00026-8.

Aparna, C., Saritha, P., Himabindu, V., Anjaneyulu, Y., 2008. Techniques for the evaluation of maturity for composts of industrially contaminated lake sediments. Waste Manag. 28 (10), 1773–1784. https://doi.org/10.1016/j.wasman.2007.07.008.

APHA, 2012. Standard Methods for the Examination of Water and Wastewater, 22nd edition. ed. American Public Health Association, Washington, D.C., USA.

Ayilara, M.S., Olanrewaju, O.S., Babalola, O.O., Odeyemi, O., 2020. Waste management through composting: challenges and potentials. Sustainability 12 (11), 4456. https://doi.org/10.3390/su12114456.

Bhatia, A., Ali, M., Sahoo, J., Madan, S., Pathania, R., Ahmed, N., Kazmi, A.A., 2012. Microbial diversity during Rotary Drum and Windrow Pile composting. J. Basic. Microbiol. 52, 5–15. https://doi.org/10.1002/jobm.201100077.

Bożym, M., Siemiątkowski, G., 2018. Characterization of composted sewage sludge during the maturation process: a pilot scale study. Environ. Sci. Pollut. Res. 25 (34), 34332–34342. https://doi.org/10.1007/s11356-018-3335-x.

Bonhotal, J., Schwarz, M., Rynk, R., Biala, J., Gilbert, J., Michitsch, R., 2022. Composting animal mortalities. The Composting Handbook. Elsevier, pp. 307–340. https://doi.org/10.1016/B978-0-323-85602-7.00004-2.

Brod, E., Oppen, J., Kristoffersen, A.Ø., Haraldsen, T.K., Krogstad, T., 2017. Drying or anaerobic digestion of fish sludge: nitrogen fertilisation effects and logistics. Ambio 46 (8), 852–864. https://doi.org/10.1007/s13280-017-0927-5.

Campanati, C., Willer, D., Schubert, J., Aldridge, D.C., 2022. Sustainable intensification of aquaculture through nutrient recycling and circular economies: more fish, less waste, blue growth. Rev. Fish. Sci. Aquac. 30, 143–169. https://doi.org/10.1080/23308249.2021.1897520.

Chiumenti, A., 2015. Complete nitrification–denitrification of swine manure in a full-scale, non-conventional composting system. Waste Manag. 46, 577–587. https://doi.org/10.1016/j.wasman.2015.07.035.

Choudhury, A., Lepine, C., Good, C., 2023. Methane and hydrogen sulfide production from the anaerobic digestion of fish sludge from recirculating aquaculture systems: effect of varying initial solid concentrations. Fermentation 9, 94. https://doi.org/10.3390/fermentation9020094.

Choudhury, A., Lepine, C., Hersom, M., Good, C., 2025. Characteristics of aquaculture sludge produced from two different fish diets and its impact on biogas production. Aquac. Eng., 102597 https://doi.org/10.1016/j.aquaeng.2025.102597.

Ekinci, K., Tosun, İ., Kumbul, B.S., Şevik, F., Sülük, K., Bıtrak, N.B., 2020. Aeration requirement and energy consumption of reactor-composting of rose pomace influenced by C/N ratio. Environ. Monit. Assess. 192, 563. https://doi.org/10.1007/s10661-020-08528-3.

El Janati, M., Robin, P., Akkal-Corfini, N., Bouaziz, A., Sabri, A., Chikhaoui, M., Thomas, Z., Oukarroum, A., 2023. Composting date palm residues promotes circular agriculture in oases. Biomass. Convers. Biorefinery 13 (16), 14859–14872. https://doi.org/10.1007/s13399-022-03387-z.

Estrella-González, M.J., Suárez-Estrella, F., Jurado, M.M., López, M.J., López-González, J.A., Siles-Castellano, A.B., Muñoz-Mérida, A., Moreno, J., 2020. Uncovering new indicators to predict stability, maturity, and biodiversity of compost on an industrial scale. Bioresour. Technol. 313, 123557. https://doi.org/10.1016/j.biortech.2020.123557.

FAO, 2024. The State of World Fisheries and Aquaculture 2024. Blue Transformation in action. Rome.

Fidanza, M.A., Sanford, D.L., Beyer, D.M., Aurentz, D.J., 2010. Analysis of fresh mushroom compost. HortTechnology 20 (2), 449–453. https://doi.org/10.21273/HORTTECH.20.2.449.

Fournel, S., Godbout, S., Ruel, P., Fortin, A., Duquette-Lozeau, K., Létourneau, V., Généreux, M., Lemieux, J., Potvin, D., Côté, C., Duchaine, C., Pellerin, D., 2019. Production of recycled manure solids for use as bedding in Canadian dairy farms: II. Composting methods. J. Dairy Sci. 102, 1847–1865. https://doi.org/10.3168/jds.2018-14967.

Gondek, M., Weindorf, D.C., Thiel, C., Kleinheinz, G., 2020. Soluble salts in compost and their effects on soil and plants: a review. Compost. Sci. Util. 28, 59–75. https://doi.org/10.1080/1065657X.2020.1772906.

Hach, 2021. DR6000 User Manual, Seventh ed. Hach Comapny, Colorado, NV, USA.

Hazarika, J., Khwairakpam, M., 2018. Evaluation of biodegradation feasibility through rotary drum composting recalcitrant primary paper mill sludge. Waste Manag. 76, 275–283. https://doi.org/10.1016/j.wasman.2018.03.044.

Ho, T.T.K., Tra, V.T., Le, T.H., Nguyen, N.-K.-Q., Tran, C.-S., Nguyen, P.-T., Vo, T.-D.-H., Thai, V.-N., Bui, X.-T., 2022. Compost to improve sustainable soil cultivation and crop productivity. Case Stud. Chem. Environ. Eng. 6, 100211. https://doi.org/10.1016/j.cscee.2022.100211.

Illera-Vives, M., Seoane Labandeira, S., Brito, L.M., López-Fabal, A., López-Mosquera, M. E., 2015. Evaluation of compost from seaweed and fish waste as a fertilizer for horticultural use. Sci. Hortic. 186, 101–107. https://doi.org/10.1016/j.scienta.2015.02.008.

Illera-Vives, M., Seoane Labandeira, S., Iglesias Loureiro, L., López-Mosquera, M.E., 2017. Agronomic assessment of a compost consisting of seaweed and fish waste as an organic fertilizer for organic potato crops. J. Appl. Phycol. 29, 1663–1671. https://doi.org/10.1007/s10811-017-1053-2.

Jain, M.S., Daga, M., Kalamdhad, A.S., 2019. Variation in the key indicators during composting of municipal solid organic wastes. Sustain. Environ. Res. 29 (1), 9. https://doi.org/10.1186/s42834-019-0012-9.

Kalamdhad, A.S., Kazmi, A.A., 2009. Effects of turning frequency on compost stability and some chemical characteristics in a rotary drum composter. Chemosphere 74, 1327–1334. https://doi.org/10.1016/j.chemosphere.2008.11.058.

Kalamdhad, A.S., Pasha, M., Kazmi, A.A., 2008. Stability evaluation of compost by respiration techniques in a rotary drum composter. Resour. Conserv. Recycl. 52, 829–834. https://doi.org/10.1016/j.resconrec.2007.12.003.

Ko, H.G., Park, S.H., Kim, S.H., Park, H.G., Park, W.M., 2005. Detection and recovery of hydrolytic enzymes from spent compost of four mushroom species. Folia Microbiol. 50 (2), 103–106. https://doi.org/10.1007/BF02931456.

Liao, P.H., Jones, L., Lau, A.K., Walkemeyer, S., Egan, B., Holbek, N., 1997. Composting of fish wastes in a full-scale in-vessel system. Bioresour. Technol. 59, 163–168.

Liu, K., Zhang, K., Li, P., Wei, X., Tang, N., Huang, X., 2026. Impact of moisture regulation methods on the fish manure composting process and gas emissions. Environ. Technol. Innov., 104748 https://doi.org/10.1016/j.eti.2026.104748.

Lv, Y., Wang, J., Chen, R., Xu, J., Xiao, N., Hou, J., He, X., 2026. Aquaculture solid waste as a nutrient-rich feedstock for sustainable compost production. Water 18 (11), 1331. https://doi.org/10.3390/w18111331.

Magdoff, F., 2021. Building soils for better crops: ecological management for healthy soils. Soil. Sci. 410. https://doi.org/10.1097/00010694-199311000-00014.

Magrí, A., Teira-Esmatges, M.R., 2015. Assessment of a composting process for the treatment of beef cattle manure. J. Environ. Sci. Health Part B 50, 430–438. https://doi.org/10.1080/03601234.2015.1011942.

Matiz-Villamil, A., Chamorro-Tobar, I.C., Sáenz-Aponte, A., Pulido-Villamarín, A., Carrascal-Camacho, A.K., Gutiérrez-Rojas, I.S., Sánchez-Garibello, A.M., Barrientos-Anzola, I.A., Zambrano-Moreno, D.C., Poutou-Piñales, R.A., 2021. Management of swine mortalities through the use of a mixed composting-accelerating bio-inoculant. Heliyon 7 (1). https://doi.org/10.1016/j.heliyon.2020.e05884.

Meena, M.D., Dotaniya, M.L., Meena, M.K., Meena, B.L., Meena, K.N., Doutaniya, R.K., Meena, H.S., Moharana, P.C., Rai, P.K., 2021. Maturity indices as an index to evaluate the quality of sulphur enriched municipal solid waste compost using variable byproduct of sulphur. Waste Manag. 126, 180–190. https://doi.org/10.1016/j.wasman.2021.03.004.

Meng, L., Li, W., Zhang, S., Wu, C., Lv, L., 2017. Feasibility of co-composting of sewage sludge, spent mushroom substrate and wheat straw. Bioresour. Technol. 226, 39–45. https://doi.org/10.1016/j.biortech.2016.11.054.

Meng, L., Zhang, S., Gong, H., Zhang, X., Wu, C., Li, W., 2018. Improving sewage sludge composting by addition of spent mushroom substrate and sucrose. Bioresour. Technol. 253, 197–203. https://doi.org/10.1016/j.biortech.2018.01.015.

Michel, F., O'Neill, T., Rynk, R., Bryant-Brown, M., Calvez, V., Li, J., Paul, J., 2022. Contained and in-vessel composting methods and methods summary. In: The Composting Handbook. Elsevier, pp. 271–305. https://doi.org/10.1016/B978-0-323-85602-7.00009-1.

Morisaki, N., Phae, C.G., Nakasaki, K., Shoda, M., Kubota, H., 1989. Nitrogen transformation during thermophilic composting. J. Ferment. Bioeng. 67 (1), 57–61. https://doi.org/10.1016/0922-338X(89)90087-1.

Morse, D.E., Friendshuh, K., Hanks, M., Iwan, R., Schmidt, D., 2001. *Composting animal mortalities*. Agricultural Development Division. Minnesota Department of Agriculture. ⟨https://www.mda.state.mn.us/sites/default/files/2018-05/compostguide.pdf⟩.

Nhut, N., Hao, N.V., Bosma, R.H., Verreth, J.A.V., Eding, E.H., Verdegem, M.C.J., 2019. Options to reuse sludge from striped catfish (Pangasianodon hypophthalmus, Sauvage, 1878) ponds and recirculating systems. Aquac. Eng. 87, 102020. https://doi.org/10.1016/j.aquaeng.2019.102020.

Ozores-Hampton, M., Biala, J., Evanylo, G., Faucette, B., Cooperband, L., Roe, N., Creque, J.A., Sullivan, D., 2022. Compost use. The Composting Handbook. Elsevier, pp. 777–846. https://doi.org/10.1016/B978-0-323-85602-7.00013-3.

Pérez-San Martín, A., Tortosa, G., González, A., Cayunao, S., Curaqueo, G., 2024. Drying treatment for sludges of the Chilean salmon farming industry and its potential as an agricultural soil amendment. Arch. Agron. Soil Sci. 70 (1), 1–18. https://doi.org/10.1080/03650340.2023.2282590.

Pérez-San Martín, A., Tortosa, G., Bustamante, M.Á., González, A., Curaqueo, G., 2025. Composting salmon farming sludge: a potential soil amendment with a focus on the circular economy approach. J. Soil. Sci. Plant. Nutr. 1–10. https://doi.org/10.1007/s42729-025-02465-1.

Ponsá, S., Pagans, E., Sánchez, A., 2009. Composting of dewatered wastewater sludge with various ratios of pruning waste used as a bulking agent and monitored by respirometer. Biosyst. Eng. 102, 433–443. https://doi.org/10.1016/j.biosystemseng.2009.01.002.

Porto, Y.D., Fogaça, F.H.D.S., Andrade, A.O., Da Silva, L.K.S., Lima, J.P., Da Silva, J.L., Vieira, B.S., Cunha Neto, A., Figueiredo, E.E.D.S., Tassinari, W.D.S., 2022. Salmonella spp. in aquaculture: an exploratory analysis (Integrative Review) of microbiological diagnoses between 2000 and 2020. Animals 13, 27. https://doi.org/10.3390/ani13010027.

Qasim, W., Lee, M.H., Moon, B.E., Okyere, F.G., Khan, F., Nafees, M., Kim, H.T., 2018. Composting of chicken manure with a mixture of sawdust and wood shavings under forced aeration in a closed reactor system. Int. J. Recycl. Org. Waste Agric. 7, 261–267. https://doi.org/10.1007/s40093-018-0212-z.

Radziemska, M., Mazur, Z., 2015. Effect of compost from byproduct of the fishing industry on crop yield and microelement content in maize. J. Ecol. Eng. 16, 168–175. https://doi.org/10.12911/22998993/59378.

Rafiee, G., Saad, C.R., 2005. Nutrient cycle and sludge production during different stages of red tilapia (Oreochromis sp.) growth in a recirculating aquaculture system. Aquaculture 244, 109–118. https://doi.org/10.1016/j.aquaculture.2004.10.029.

Rynk, R., 1992. On-farm composting handbook. Natural Resource. Agriculture, and Engineering Service, Ithaca, NY.

Rynk, R., Schwarz, M., Richard, T.L., Cotton, M., Halbach, T., Siebert, S., 2022. Compost feedstocks. The Composting Handbook. Elsevier, pp. 103–157. https://doi.org/10.1016/B978-0-323-85602-7.00005-4.

Sánchez-Monedero, M.A., Roig, A., Paredes, C., Bernal, M.P., 2001. Nitrogen transformation during organic waste composting by the Rutgers system and its effects on pH, EC, and maturity of the composting mixtures. Bioresour. Technol. 78 (3), 301–308. https://doi.org/10.1016/S0960-8524(01)00031-1.

Sharma, D., Saadi, I., Oazana, S., Lati, R., Laor, Y., 2024. Distribution of residence time in rotary-drum composting and implications for hygienization. Waste Manag. 179, 22–31. https://doi.org/10.1016/j.wasman.2024.02.047.

Sommer, S.G., Dahl, P., 1999. Nutrient and carbon balance during the composting of deep litter. J. Agric. Eng. Res. 74 (2), 145–153. https://doi.org/10.1006/jaer.1999.0446.

Soriano-Disla, J.M., Gómez, I., Navarro-Pedreño, J., 2010. Assessment of the evolution and efficiency of a full-scale sewage sludge composting process. Compost. Sci. Util. 18, 81–88. https://doi.org/10.1080/1065657X.2010.10736939.

Stehouwer, R., Cooperband, L., Rynk, R., Biala, J., Bonhotal, J., Antler, S., Lewandowski, T., Nichols, H., 2022. Compost characteristics and quality. The Composting Handbook. Elsevier, pp. 737–775. https://doi.org/10.1016/B978-0-323-85602-7.00012-1.

Stelmachowski, M., Jastrzębska, M., Zarzycki, R., 2003. In-vessel composting for utilizing of municipal sewage-sludge. Appl. Energy 75, 249–256. https://doi.org/10.1016/S0306-2619(03)00038-2.

Thompson, W., Leege, P., Millner, P., Watson, M., 2001. Test Methods for the Examination of Composting and Compost. The United States Department of Agriculture.

Timmons, M.B., Vinci, B.J., 2022. Recirculating Aquaculture, fifth ed. Ithaca Publishing Company LLC, New York.

Toledo, M., Márquez, P., Siles, J.A., Chica, A.F., Martín, M.A., 2019. Co-composting of sewage sludge and eggplant waste at full scale: feasibility study to valorize eggplant waste and minimize the odoriferous impact of sewage sludge. J. Environ. Manag. 247, 205–213. https://doi.org/10.1016/j.jenvman.2019.06.076.

US Composting Council, 2020a. Consumer Compost Use Program - Establishment and Maintenance: Trees and Shrubs Class.

US Composting Council, 2020b. Consumer Compost Use Program - Establishment and Maintenance: Flower and Vegetable Garden Class.

US Composting Council, 2020c. Consumer Compost Use Program - Establishment and Maintenance: Lawn Class.

US EPA, 1993. Part 503 - Standards for the use or disposal of sewage sludge, Code of Federal Regulations.

USDA-NRCS, 2010. Chapter 2: Composting, in: Part 637 Environmental Engineering National Engineering Handbook.

Vázquez, M.A., De La Varga, D., Plana, R., Soto, M., 2015. Integrating liquid fraction of pig manure in the composting process for nutrient recovery and water re-use. J. Clean. Prod. 104, 80–89. https://doi.org/10.1016/j.jclepro.2015.05.016.

van Rijn, J., 2013. Waste treatment in recirculating aquaculture systems. Aquac. Eng. 53, 49–56. https://doi.org/10.1016/j.aquaeng.2012.11.010.

Vatansever, R., Ozyigit, I.I., Filiz, E., 2017. Essential and beneficial trace elements in plants, and their transport in roots: a Review. Appl. Biochem. Biotechnol. 181, 464–482. https://doi.org/10.1007/s12010-016-2224-3.

Wu, D.L., Liu, P., Luo, Y.Z., Tian, G.M., Mahmood, Q., 2010. Nitrogen transformations during co-composting of herbal residues, spent mushrooms, and sludge. J. Zhejiang Univ. Sci. B 11 (7), 497–505. https://doi.org/10.1631/jzus.B0900271.

Zhang, K., Zheng, J., Liu, K., Gao, L., Bi, R., Ji, F., 2026. Optimizing intermittent rotary aeration to enhance efficiency and reduce greenhouse gas and ammonia emissions during fish manure composting. J. Environ. Manag. 398, 128414. https://doi.org/10.1016/j.jenvman.2025.128414.

Zhang, L., Sun, X., 2014. Changes in physical, chemical, and microbiological properties during the two-stage co-composting of green waste with spent mushroom compost and biochar. Bioresour. Technol. 171, 274–284. https://doi.org/10.1016/j.biortech.2014.08.079.