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Open windrow composting of fish waste in Estonia

M. Lanno[1,*], M. Silm[2], M. Shanskiy[1], A. Kisand[2], K. Orupõld[3] and M. Kriipsalu[4]

[1]Estonian University of Life Sciences, Institute of Agricultural and Environmental Sciences, Chair of Soil Science, Fr.R. Kreutzwaldi 5, EE51006 Tartu, Estonia
[2]Estonian University of Life Sciences, Institute of Agricultural and Environmental Sciences, Chair of Hydrobiology and Fishery, Fr.R. Kreutzwaldi 5, EE51006 Tartu, Estonia
[3]Estonian University of Life Sciences, Institute of Agricultural and Environmental Sciences, Chair of Environmental Protection and Landscape Management, Fr.R. Kreutzwaldi 5, EE51006 Tartu, Estonia
[4]Estonian University of Life Sciences, Institute of Forestry and Rural Engineering, Chair of Rural Building and Water Management, Fr.R. Kreutzwaldi 5, EE51006 Tartu, Estonia
[*]Correspondence: marge.lanno@emu.ee

Abstract. By-catch fish is caught unintentionally during the fishing and is currently thrown back in water bodies to cause the water pollution. Currently fishermen does not have a motivation to bring the by-catch fish to the shore, as it needs to be sorted by fish species, causing fishermen extra work without additional income. Estonian Ministry of Rural Affairs decided to give funding to present study with purpose to find solution to this matter. One possible solution for by-catch fish utilization is to produce high value nutrient rich fertilizer in order to close nutrient cycle and return valuable nutrients into soil. The adaptive study of outdoor windrow composting was conducted with consecutive treatments, rather than simultaneously, in order to make adaptive improvements to the set-up of each consecutive treatment. The consecutive treatments showed that fish waste composting is manageable from a technical perspective, feasible in a temperate climate, and that this type of compost holds high potential as an organic fertiliser or soil improver. Composting process started rapidly and, as required by the EU Commission regulation EU 142/2011, temperatures exceeded 70 °C for at least 1 h in all windrows. While initial treatments suffered from odours, as well as events inhibitive to the composting process, these disadvantages were successfully avoided in later treatments by adding a biofilter and inoculant from previous composting windrows, as well as lake sediments. Rather than disposing of low-value fish, these can be recycled into stable and nutrient-rich compost on-site, near fishing harbours.

Key words: by-catch, biofilter, clay minerals, lake sediment, organic fertiliser, wheat straw.

INTRODUCTION

Composting is an aerobic microbial process that turns organic material into stable humus-like material that can be used to improve soil texture and nutrient content for agricultural use. Composting is suitable for treating different kinds of organic wastes such as food waste, manure, green wastes or municipal solid wastes (Rynk, 1992;

Awasthi et al., 2020). Composting can be performed with different technologies, and at different scales (Rynk, 1992; Hobson et al., 2005). In Estonia, composting is mostly done in open windrows, which are periodically mixed in order to improve porosity and oxygen supply. Mainly source-separated municipal biowaste is composted in Estonia (BEU, 2020), sometimes in combination with garden waste and animal by-products. National end-of-waste regulations for biowaste compost (BEU, 2020) and sewage sludge compost quality (Regulation, 2017) have been enforced since 2013 and 2017, respectively.

Nutrient rich compost holds high potential as an organic fertiliser or soil improver, offering the possibility to reduce the use of synthetic fertilisers. Although fish waste composting is not yet included in local waste management plans in Estonia, there is growing interest for fish waste valorisation and associated nutrient recycling. The topic was also prioritised by the Estonian Ministry of Rural Affairs, through the decision to fund the present study, with the aim of finding new solutions regarding fish waste management. Both the waste from fish processing, as well as by-catch, could represent inputs for composting. For example, Lake Võrtsjärv represents approximately 8% of commercial fishing in Estonian lakes and rivers. In 2018, it was estimated that, for each kg of commercial catch, there were approximately 1.45 kg of by-catch, resulting in 6,300 tons of by-catch per year (Bernotas et al., 2018). During the years 2008–2017, the yearly average commercial catch for Estonian lakes and rivers was 2,800 tons, 65,000 tons for the Baltic Sea and 12,500 tons for the Atlantic Ocean (Quarterly bulletin…., 2018). In Estonia, similar to Baltic region as a whole, fisheries represent an important part of the economy; thus, fish waste composting should be included in local waste management plans.

Besides leftovers from the fish industry, a significant source of unwanted fish is by-catch. By-catch includes fish caught of unusable size, damaged fish and species without economic value (Clucas, 1997). Rather than being revalued, by-catch in Estonia is often thrown back into the aquatic environment, where it results in pollution.

Long-term cultivation and fertilisation both affect the humus content in soils (Hospodarenko et al., 2018). Also, mineral sources for phosphorus (P) fertilisers are located in sensitive regions, or generate a large ecological footprint during transportation to agricultural fields (Roy et al., 2005). Therefore, the available of local P nutrient sources is vital. Compost can add humus to soils over a longer period, and reduce the need for using synthetic fertilisers (Epstein, 2017). Compost represents a slow-release fertiliser, as nutrients from composted material are released slowly yet consistently, thus building up a stable reserve of soil nutrients (Hepperly et al., 2009).

It has been claimed that fish-derived amendments behave like slow-release nitrogen (N) fertilisers, and hold higher P release capacities, as well as being rich in calcium (Ca) (Laos et al., 2000). Therefore, fish waste could be processed into a nutrient-rich soil amendment. There have been different composting trials indicating that fish waste compost represents a suitable fertiliser for agricultural use, and can increase crop yield (Laos et al.,1998; López-Mosquera et al., 2011; Illera-Vives et al.,2015; Radziemska et al., 2018).

Due to problematic odour emission, fish waste must be stabilised rapidly. One key factor may be choosing an appropriate compost mixture. In addition to organic wastes, different substrates such as bulking agents and other additives must be used while creating compost windrows. Shredded wood and straw are porous and rich in carbon

(C), and can improve aeration and moisture regulation, as well as improve odour absorption (Rynk, 1992). Sufficient aeration is necessary, as a limited oxygen (O_2) supply during the active composting period decreases microbial activity, inhibiting the composting process (Avnimelech et al., 2004). To understand the progression of composting, O_2 consumption must be measured. Respiration rate reflects microbial activity and the decomposition of organic matter. Accordingly, higher O_2 consumption is associated with higher microbial activity. In stable or mature compost, easily degradable organic matter is decomposed, and the resulting compost is safe to use (Wichuk & McCartney, 2013). Moisture content is also important, as water transports dissolved nutrients to microorganisms, resulting in greater microbial activity, which is essential for the decomposition process.

Straw as a bulking agent is light and fluffy, making the windrows porous. Also, it biodegrades more easily than wood chips. This may be the result of higher undesirable ammonia (NH_3) emission; but at the same time, it has been demonstrated that composts with straw amendments contain higher nutrient concentrations than those with wood chips (Sardá et al., 2019).

In order to improve the composting process, different additives such as biochar, peat, clay minerals and mature compost can be added into fresh composting mixtures, with the purpose of reducing gas- and odour emissions, as well as to increase the nutrient content of the final product, thus influencing microbial activity. As a result, the degradation process starts earlier and the thermophilic phase lasts longer (McCrory & Hobbs, 2001; Gabhane et al., 2012; Sánchez-García et al., 2015; Barthod et al., 2018). Additives such as clay minerals can also limit water loss and reduce greenhouse gas emissions (Barthod et al., 2016). It has been shown that an adequate moisture content has have a greater influence than temperature on the decomposition process (Liang et al., 2003); an adequate moisture level in compost is approximately 40–60% (Rynk, 1992). Clay minerals can also influence microbial activity, as clay provides a pH suitable for sustainable microbial growth (Stotzky & Rem, 1966).

Temperature is an important indicator for the composting process, reflecting both the degradation of organic matter and microbial activity (Eklind et al., 2007). The thermophilic phase occurs when temperatures inside compost windrows exceed 40 °C; where the organic matter decomposition process is the fastest at 55 °C (Eklind et al., 2007; Rynk, 1992), when microbial activity is highest (Miyatake & Iwabuchi, 2005).

Compost must be safe for humans and the environment, and therefore it must be free of pathogens. Because of its status of being animal by-products (ABPR), temperatures must exceed 70 °C for 1 h for sanitation purposes, as required by the EU Commission regulation EU 142/2011 (European Commission, 2011). After the active composting period, it is necessary to let compost mature, as immature compost may inhibit plant growth (Ozores-Hampton et al., 2002).

The aim of this study was to develop a practical technological solution for composting, whereby fishermen can use nearby fishing harbours to revalue by-catch fish, allowing this resource to be converted into nutrient rich fertiliser suitable for agricultural use. We focused particularly on solutions for reducing odours and meeting sanitation requirements.

MATERIALS AND METHODS

Composting experiment

The composting experiment was conducted in Taali, Pärnu County, Estonia. Five batches of fish compost (corresponding to treatments F1–5), each having different raw material ratios, were composted from spring 2018 to autumn 2019 (Table 1). Treatments were performed consecutively, rather than simultaneously, in order to make adaptive improvements to the set-up of each consecutive treatment. The composting site was on a concrete surface, in order to prevent soil- and groundwater pollution. All windrows were covered with the semi-permeable geotextile KSV 200 (Compost Systems, Austria), in order to reduce the weather impact, maintain the in-compost microclimate, and protect the windrows from animals. All treatments were carried out at a scale 10 m^3 (12–16 m long and 1.5 m wide windrows). The main component in each compost mixture was low-value by-catch fish from Lake Võrtsjärv, followed by wheat straw as bulking material, as it is considered easily available.

Table 1. Initial ingredients of compost mixtures (kg). F1–5 represent different treatments (windrows). An asterisk (*) indicates that the straw was shredded

Windrow	By-catch fish	Straw	Water	Peat	Mature compost (horse manure)	Mature compost (fish, F1 treatment)	Lake sediment
F1	4,406	1,125	0	0	0	0	0
F2	1,705	1,312	1,860	0	0	0	0
F3	930	943	1,996	960	913	545	0
F4	905	1,155*	1,150	0	0	0	355
F5	960	1,347*	1,200	0	0	460	180

For treatments F1, F2 and F3, unshredded wheat straw was used; whereas in treatments F4 and F5, wheat straw was shredded with the trailed straw chopper PRIMOR 5570 M (KUHN Group, Austria).

Additives such as peat, mature compost (used as inoculant), and lake sediment rich in clay minerals, containing 6 g of clay material per 100 g dry matter (DM), were used in different treatments. All by-catch and lake sediment originated from Lake Võrtsjärv. Straw was collected in 2017 from the surrounding agricultural fields in in Taali, Pärnu County, Estonia. The straw was subsequently dried and pressed into 250 kg rolls. The by-catch fish samples, and straw, were analysed for total C and N in order justify an appropriate balance of material inputs. The calculations were based on the assumption, that efficient composting process takes place, when C/N is (20–30)/1. Composting materials were mixed together using a BVL van Lengerich feed mixer V-Mix 13 2S plus (BVL Group, Germany).

Different treatments lasted for different lengths of time, as treatments F2 and F3 were conducted during autumn, resulting in shorter period of time suitable for maturation process (Table 2).

Table 2. Composting treatments. F1–5 represent different treatments (windrows)

Windrow	Composting duration (d)	Moisture adjustment	Moisture adjustment	Turning frequency
F1	185	No	No	Day 35
F2	70	Yes	Days 1, 9	Days 9, 11, 14, 16 and 19
F3	50	Yes	Day 1	Days 5, 8, 11 and 22
F4	135	Yes	Days 1, 9	Days 6, 9, 15, 18, 25 and 40
F5	135	Yes	Days 1, 9	Days 6, 9, 15, 18, 25 and 40

Temperature was measured automatically from windrows F2, F3, F4 and F5, using thermocouple wires (type K, min -10 °C, max 105 °C, 2-Core, Unscreened, PVC-insulated, 100 m; Thermosense, UK). Depending on treatment, 2 or 3 sensors were inserted into each windrow, approximately 20 cm up from concrete surface. Carbon dioxide (CO_2) concentration was measured manually twice a day, using a Brigon Testoryt CO_2 detector (0–20%; Brigon Messtechnik, Germany). When temperatures exceeded 70 °C for several days, or CO_2 concentration rose above 10%, windrows were mixed using either a Backhus 16.30 windrow turner (Eggersmann, Germany) or an ST 300 windrow turner (COMPOST and WASTE technology, Austria).

To prevent odours, a biofilter was associated with each treatment (Fig. 1). The biofilter was made from a 1 m^3 container filled with a 4:1:1 ratio of shredded wood, coal and mature compost of horse manure, respectively; and was connected to its respective windrow via a 75 mm polyethylene aeration pipe perforated with 5 mm diameter holes spaced 10 cm apart, the holes forming two shifting lines. Negative pressure via fan was used for ventilation. Biofilters were turned on twice a day for 15 min, until problematic odours discontinued (4 to 5 days). The same biofilter was used for each treatment.

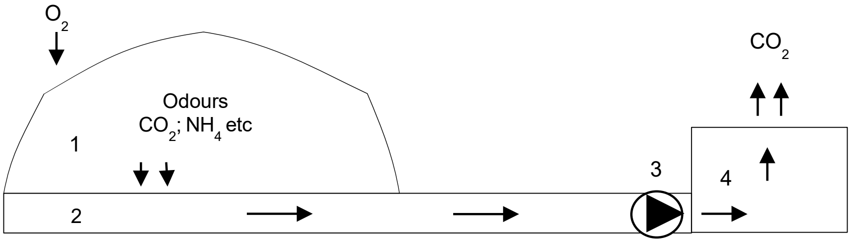

Figure 1. Biofilter- and windrow schematic: 1 – compost windrow; 2 – perforated pipe under the windrow; 3 – fan; 4 – biofilter.

Chemical analyses

Compost samples were collected from all treatments, from three different locations approximately 20–30 cm into the windrow. From each sample, approximately 250 g was homogenised, dried at 105 °C and ball-milled prior to analysis. DM- and ash concentrations were measured. P, potassium (K), Ca and magnesium (Mg) content was determined using the ammonium lactate (AL) method from Egnér et al. (1960); and C and N content was analysed using a VarioMAX CNS analyser (ELEMENTAR, Germany).

Compost stability

Four-day cumulative oxygen consumption was determined via manometric respirometry (OxiTop, WTW, Germany) according to the manufacture´s recommendations. Measurements were collected in 1 L air-tight containers with 50–60 g of fresh sample. Since produced CO_2 was removed by absorber (2 M NaOH), the oxygen consumption of samle could be calculated from the pressure drop in the container. Measurements were collected in triplicate at 20 °C in a climate chamber (Sanyo MLR-351H, Osaka, Japan), in total darkness.

Statistical analyses

A three-way analysis of variance (ANOVA) was performed in order to examine the effect of treatment, ambient temperature, duration of composting, and the interactions between these factors, on composting temperature. A one-way ANOVA was used to study the effect of treatment on mean temperature. A post-hoc Tukey *HSD* analysis was performed for pairwise comparisons, using the package 'agricolae' (Mendiburu, 2015) in R.

RESULTS AND DISCUSSION

Composting process

In all treatments, the thermophilic phase was reached in 1 to 2 days, and temperatures exceeded 70 °C, as required by the EU Commission regulation EU 142/2011 on animal by-products. The duration of thermophilic phase was treatment-dependent. After the thermophilic phase, temperatures decreased rather quickly, and ambient levels were reached within days (Table 3).

Table 3. Temperature characteristics: n.d. – data not determined; * – temperature fluctuation. In F2 treatment temperature decreased < 35 °C several times since day 6 and rised again after mechanical mixing with windrow turner

Batch Windrow	Time to reach > 45 °C	Number of days temp > 45 °C	Number of days temp > 70 °C	Peak temp °C	Time to reach the peak temp	Time to drop to ambient level < 35 °C
F1	n.d	n.d	n.d	n.d	n.d	n.d
F2	Day 1	14	1	72.9	Day 1	Day 6*
F3	Day 2	21	7	76.4	Day 6	Day 23
F4	Day 1	63	18	75.0	Day 7	Day 63
F5	Day 2	69	21	78.6	Day 8	Day 73

In treatment F1, a windrow turner was used for mixing the compost ingredients. We do not recommend this method for preparing compost mix with fish, as whole fish were thrown from the windrow.

In deeper layers of the F1 windrow, fish started to slow-cook as a result of high temperatures; and in outer layers of this windrow, fish became either dried or rotted. To prevent the spread of odours, the F1 windrow was covered with peat for 2 weeks, starting on day 7. It was concluded that the wheat straw is suitable as bulking material, but as it is too dry, water should be added at the beginning of the composting process. Also, shredding of fish would speed up degradation. As the feed mixer later partly shredded the fish, it made the compost mixture more homogeneous.

When compiling the F2 treatment, water was added to the compost mixture. Since, due to fish decomposition, there was a considerable problem with fish odour emission from treatment F1, a biofilter was implemented in treatment F2. Initially, the biofilter was turned on for 15 min every 2 h, which caused the temperature drop in the windrow. It was concluded that the optimal biofilter working mode was twice a day for 15 min. The biofilter also provided a sufficient O_2 supply to windrow, thus reducing the need for mechanical mixing of windrows during the first days.

In treatment F2, the thermophilic phase was reached at the end of the day 1. For unknown reasons, the temperature started to decrease after day 5 (Fig. 2). After the temperature decreased, the windrow was mixed with the windrow turner. This resulted in a temporary rise in temperature. Temperatures in the treatment F2 windrow exceeded the thermophilic phase threshold for 16 days (Table 3). These high temperatures in compost are associated with microbial activity, and therefore temperature decreases are frequently influenced by low microbial activity (Alves et al., 2019; Wichuk & McCartney, 2013). This may have been the cause of temperature fluctuation in the treatment F2 windrow. However, the cause of low microbial activity is unclear, as easily-biodegradable substrate was not consumed until the end of the active composting period, and neither O_2 supply nor moisture content were not considered to be limiting factors. Further research is needed to conclude what causes these types of temperature fluctuations.

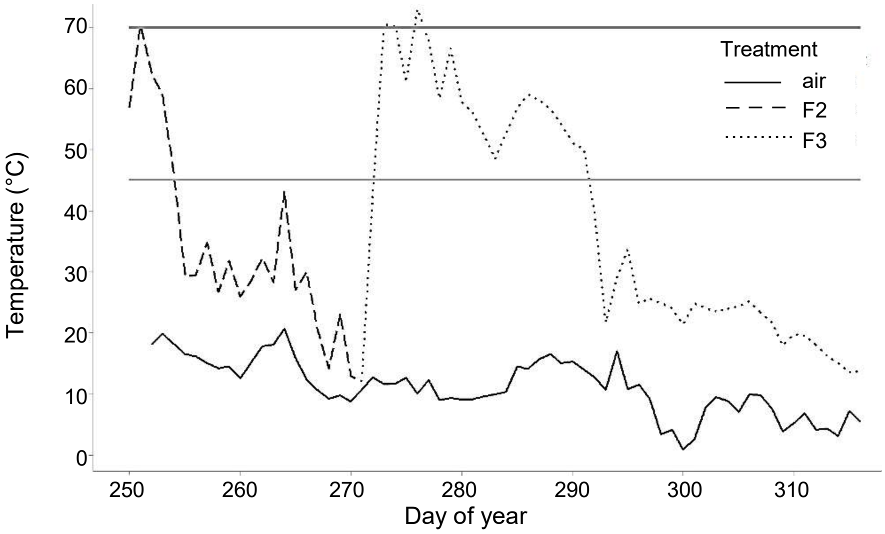

Figure 2. Windrow F2 and F3 temperature graphs from year 2018.

It was previously shown that the addition of mature compost can slightly increase temperature in the thermophilic phase (Maeda et al., 2009). For the purpose of stabilising temperatures during the active composting period, as well as to add more beneficial bacteria necessary for the decomposition process, peat and mature compost were added to treatment F3. The thermophilic phase for this treatment was reached by day 3, and temperatures were stable during the active composting period, which lasted for 23 days. As temperatures inside compost are not uniform (Avnimelech et al., 2004), the treatment

F3 windrow was mixed during days 5 and 8, in order to homogenise temperature and moisture. After turning the compost, temperatures inside the F3 windrow decreased for an hour, but then started to increase again. Similar behaviour has registered by Marešová & Kollárová, (2010). In their study they also noticed, that after mechanical mixing temperature decreased in the windrow, but after some time temperature started to increase, exceeding the previous level.

For treatments F4 and F5, both windrows contained by-catch fish, shredded straw and lake sediment; but in treatment F5, mature compost was also added. The mean in-windrow temperatures, between treatments F4 and F5, were not statistically different, even though the temperatures in F5 were slightly higher than in F4 (Fig. 3). In windrows of both F4 and F5, the thermophilic phase was reached by the end of day 1. Furthermore, temperatures > 65 °C lasted longer than in the previous treatments. In treatment F2 and F3, the thermophilic period lasted 14 and 21 days, respectively; while in treatments F4 and F5, the thermophilic period lasted 63 and 69 days, respectively (Table 3). Temperatures decreased to ambient levels in treatment F4 after day 63, and in F5 after day 73. While it has been reported that the decomposition process is most efficient at 55 °C (Eklind et al., 2007), our temperatures exceeded 70 °C for a long period, yet decomposition was still efficient. However, it should be considered that gas emissions can be more intense at higher temperatures (Eklind et al., 2007), and the metabolic activity of many microorganisms will decrease when temperatures exceed 60 °C (Miyatake & Iwabuchi, 2005).

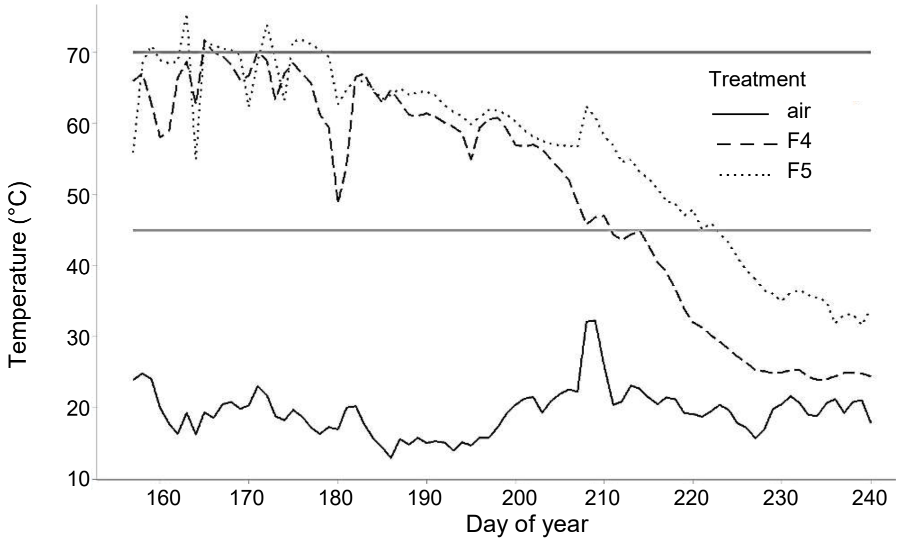

Figure 3. Windrow F4 and F5 temperature graphs from year 2019.

A more efficient composting process in treatments F4 and F5 can be attributed to the addition of shredded straw, which is readily degradable. In the first treatments (F1, F2 and F3), unshredded straw did not completely degrade, and was visible in the final compost product. Straw contains a large fraction of cellulose (29–35%), hemicellulose (26–32%) and lignin (16–21%) (Kapoor et al., 2016), for which decomposition is relatively slow (Eklind et al., 2007). Another explanation for more active composting process can be explained with the addition of clay minerals from lake sediments. Compost constituents were better bound together, making the mixture more homogeneous and providing better conditions for decomposition. It has been shown that the addition of clay minerals can increase water retention capacity and binding the organic material of composting mass (Chen et al., 2018). Therefor adding clay minerals assures the better conditions for microbial activity, resulting in higher temperatures and a longer duration of the thermophilic phase.

Compost stability

According to the Estonian regulation for sewage sludge compost, compost is referred as stable if O_2 consumption over 4 days is less than 10 mg O_2 g^{-1} DM (Regulation, 2017). These values in treatments F2 and F3 remained slightly over the given limit (Fig. 4). Unstable compost can produce odours, generate harmful compounds and, depending on the plant variety, reduce seed germination and inhibit plant growth (Mathur et al., 1993; Emino & Warman, 2004; Harrison, 2008). Temperature fluctuation in the treatment F2 windrow indicated unstable microbial activity during the composting process, resulting in a higher amount of undecomposed organic matter, as well as a higher respiration rate. Treatment F1, F4 and F5 windrows were very stable; their oxygen consumption was less than 5 mg O_2 g^{-1} DM, indicating that composts with longer maturation periods are more stable and safe to use.

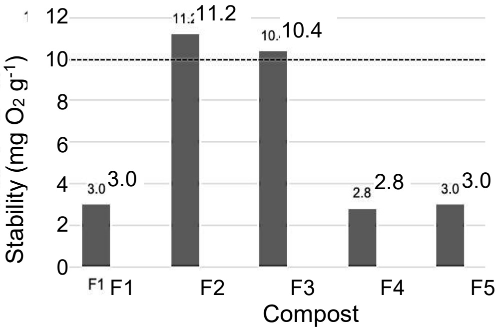

Figure 4. Compost stability determined as 4-days oxygen consumption. Values < 10 mg O_2 g^{-1} DM indicate stabile compost according to Estonian regulation for sewage sludge compost (Regulation, 2017).

Quality of composting process

The effect of treatment, ambient temperature and composting duration on composting temperature was significant ($P < 0.05$) (Table 4).

Table 4. Results of the three-way analysis of variance (ANOVA), testing the effect of treatment (TR), ambient temperature (AT), length of the composting duration (TIME), and the interactions between these factors, on composting temperatures

	Df	Sum of Square	Mean Square	F value	Pr (>F)	
TR	3	1,154,750	384,917	3,891.97	$< 2e^{-16}$	***
TIME	1	1,732,648	1,732,648	17,519.15	$< 2\times10^{-16}$	***
AT	1	27,913	27,913	282.23	$< 2e^{-16}$	***
TR × TIME	3	195,880	65,293	660.19	$< 2e^{-16}$	***
TR × AT	3	41,251	13,750	139.03	$< 2e^{-16}$	***
TIME × AT	1	17,517	17,517	177.12	$< 2e^{-16}$	***
TR × TIME × AT	3	5,178	1,726	17.45	$2.66e^{-11}$	***
Residuals	11,465	1,133,890	99			

Stars indicate significance: *** – 0.001.

Properties of compost

There were significant differences in P, K and Mg concentrations between treatments ($\alpha = 0.05$). Treatment F4 and F5 windrows had significantly different nutrient contents of P and Mg, compared to other treatments. Compared to other types of compost (e.g. made from horse manure, sewage sludge and green waste), fish compost contains considerably more P (488–918 mg 100 g^{-1}; author's unpublished data; Table 5. This could support the argument that clay minerals bind nutrients together, increasing nutrient content in the final product. It has been shown that fish waste is rich in nutrients such as P and Ca. Fish-derived amendments behave as slow-release N fertilisers, and have high P release capacity (Laos et al., 2000). Therefore, fish compost can be an important source of P based on excavated non- renewable mineral resources.

Table 5. Nutrient concentration (mg 100 g^{-1}) of fish (F1-F5), horse manure (HM), sewage sludge (SS) and green waste (GW) composts. Different letters indicate different groups according to Tukey *HSD* test ($\alpha = 0.05$)

Compost	P	K	Ca	Mg
F1	639^{b}	791^{cd}	4,471^{ab}	703^{a}
F2	593^{bc}	1,329^{bc}	4,626^{ab}	664^{a}
F3	488^{c}	1,676^{b}	3,166^{ab}	680^{a}
F4	802^{a}	668^{cd}	2,680^{ab}	291^{c}
F5	919^{a}	1,031^{cd}	2,927^{ab}	301^{c}
HM	136^{d}	2,551^{a}	2,986^{ab}	649^{a}
SS	118^{d}	552^{d}	1,170^{b}	518^{b}
GW	115^{d}	552^{d}	6,682^{a}	224^{c}

Total N concentration in treatment windrows varied from 2.43–2.77%, while total N in alternative composts varied from 0.6–3.74%. Fish composts and horse manure compost had the most similar total N concentrations (Table 5). Brinton & Seekins (1994) have stated previously, that total N concentration of fish compost is 1.29% after 60 days of composting and 1.15% when compost was mature over-winter.

One possibility for assessing potential N availability is to observe the C:N ratio of the compost, as it has been shown that available N should be present if the C:N ratio is less than 20:1 (Harrison, 2008). The C:N ratios in various composts were less than 20:1, with the exception of green waste compost (Table 6). Our results are in agreement with the idea that composts made primarily from green waste are nutrient-poor (Harrison, 2008).

Table 6. Total C and N concentration (%) and C:N ratios of fish (F1-F5)-, horse manure (HM)-, sewage sludge (SS)- and green waste (GW) composts

Compost	C%	N%	C:N
F1	30.22	2.43	12.44
F2	33.04	2.75	12.01
F3	35.66	2.73	13.06
F4	27.92	2.77	10.08
F5	27.64	2.74	10.09
HM	30.99	2.47	12.55
SS	27.02	3.74	7.22
GW	13.35	0.60	22.25

CONCLUSIONS

Fish waste can be processed into nutrient-rich soil amendments via the simple method of composting in windrows, which can be performed near fishing harbours. Fish compost is particularly rich in P and Ca. We suggest mixing fish compost ingredients with a feed mixer or similar mixing equipment, and to use a biofilter with negative aeration in order to reduce odours. Different additives, especially lake sediment with clay minerals, enhances the efficiency of the composting process. The thermophilic phase was reached in treatment windrows within 1–2 days, and temperatures exceeded 70 °C for at least 1 h, as required by the biofilter EU Commission regulation EU 142/2011 on animal by-products. Our work indicates that nutrient rich compost holds high potential as an organic fertiliser and soil improver, offering the possibility to reduce the use of synthetic fertilisers.

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