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Co-composting of Sewage Sludge, Green Waste, and Food Waste

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ABSTRACT

Rapid population growth requires more intense production of food industry, with two major consequences: significant amount of food processing residues and more sewage sludge originating from biological wastewater treatment plant. Sludge is a big concern for the disposal for wastewater treatment plant. The European Union makes an effort regarding the reduction of organic fractions disposed at a landfill. Composting is a cost-effective and ecological-friendly alternative for managing biodegradable organic fractions. Experiments of co-composting of sewage sludge, green waste and food waste, at carbon/nitrogen ratios 8.75, 18.00 and 24.90, were performed during three months by monitoring of temperature, pH, moisture, carbon and nitrogen proportion, carbon/nitrogen ratio, and germination index. The results showed that co-composting of sewage sludge, green waste and food waste is effective and results in the production of quality compost.

KEYWORDS

Co-composting, Sewage sludge, Green waste, Food waste, Carbon/Nitrogen, Waste reduction.

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INTRODUCTION

Garden and food waste contribute approximately to 30-40% of total municipal waste in the European Union [1]. Municipal solid waste contains a high proportion of organic materials, from 50% to 65% [2]. Since 1999 member states of the European Union are urged to decrease the quantity of the biodegradable waste at the landfill [3] and encouraged to sort waste at the origin, recycle and recovery [4] to meet the goals for recycling and renewable energies [1]. A huge problem worldwide is the disposal of wastewater treatment sludge [5] because of increasing amount and continuous production [6]. Sludge might be an alternative source of soil organic matter [7], however, sewage sludge should be stabilized and sanitized before application on agricultural soil.

Composting, a low-cost and simple way for managing the organic waste [8] is a technique of biological waste transformation by naturally occurring microorganisms, in the presence of oxygen and under thermophilic conditions [9]. Composting is characterized by decomposition and stabilization of the organic matter. Compost, the final product, is stable and without pathogens [10], and can be used for land amendment in agriculture [1].

Substrate characteristics, such as nutrient composition, size of the particles and ratio C/N (carbon to nitrogen), as well as process conditions, such as aeration, moisture content, temperature and pH, affect the composting process. C/N ratio in the range from 25 to 30 is generally recognized as optimal [11], as well as 25-35 [12]. However, some authors suggest C/N ratio of 15 [13], higher than 18 [14], and 20 [15] sufficient for effective composting .

Co-composting (composting two or more organic wastes) was the subject of numerous studies, as follows: co-composting of green waste and food waste, raked leaves and grass clippings at C/N ratios 13.9-19.6 [11], yard waste and food waste at ratios 70%:30%, 80%:20%, 90%:10%, and 100% yard waste [16], kitchen waste and different bulking agents (cornstalks, sawdust, and spent mushroom substrate) [17]; food waste, green waste and sewage sludge in different proportion: sewage sludge (20-40%), green waste (40-50%) and food waste (10-40%) at C/N ratios 20.9-24.7 [6], sewage sludge (30-86%), green waste (14-35%) and food waste (0-55%) at C/N ratios 11.61-19.87 [18]; wastewater treatment sludge with different bulking agents, such as freshly collected yard trimmings originating from a city collection, yard trimmings of similar origin but stored for three weeks in static piles, crushed wood pallets and deciduous tree bark [5], straw and sawdust [19], crushed wood pallet, pine bark and corn stalk [20], wheat straw, plane leaf, corncob and sunflower stalk [21], and maize straw [22].

The composting of sewage sludge is quite a challenge due to low C/N ratio, high density structure and it must be free of pathogens prior to use as fertilizer [19]. Since the characteristics of sewage sludge and urban untreated waste are opposite: low C/N ratio, dense structure and high moisture vs. high C/N ratio and low density, the bulking agents such as green waste – adsorbent are an advantageous option for soaking up the moisture of the sewage sludge. The inclusion of bulking agents into composting substrate [5] boosts the aeration rate [20], especially in natural, non-mechanical aeration systems, since it increases the composted material porosity, proven in the study of wastewater treatment sludge composting and different bulking agents [21] and with maize straw as bulking agent [22].

The aims of this research of co-composting of sewage sludge, green waste and food waste were:

- estimating the possible mixing of green waste, sewage sludge and food waste for efficient co-composting, especially at low C/N;
- assessing the impact of different initial C/N ratios on the effectiveness of the co-composting process, based on physical/chemical properties of waste; and
- evaluation of produced composts for use in agriculture.

MATERIALS AND METHODS

The set-up of the experiments of the co-composting process, the characteristics of composting mixtures, and analytical methods are described below.

Composting process

For the experiments of the co-composting (Table 1), unprocessed food waste (FW) collected from household, green waste (GW) from municipal biodegradable waste (branches, leaves, wood waste from gardens and parks) and stabilized sewage sludge (SS) from wastewater treatment plant (WWTP) Koprivnica, Croatia (Table 2 and Table 3), were used. The household food waste was chopped up manually, and the green waste was chopped up with shredder for branches to approximately 5 cm, in order to accelerate stabilization [23]. Experiments were performed as static piles with manual turning.

Table 1. Characteristics of the composting mixtures SS+GW, SS+GW+FW and SS+FW

	Mixture SS+GW	Mixture SS+GW+FW	Mixture SS+FW
waste	SS/GW	SS/GW/FW	SS/FW
ratio	30:70 v/v	30:50:20 v/v	70:30 w/w
pH	7.05	7.20	6.47
temperature[°C]	22.00	25.20	20.40
moisture[%]	50.80	59.25	54.50
organic C[%] (dry weight)	39.45	36.26	24.40
total nitrogen[%] (dry weight)	1.58	2.01	2.79
C/N ratio	24.90	18.00	8.75

Table 2. Physico-chemical composition of aerobic stabilized sludge (mean ± standard deviation, n=3)

parameter	value
pH (10% eluate)	7.62±0.13
[%] H_2O	68.00±3.00
[%] ash (550 °C) (dry weight)	56.00±2.00
[%] volatile solids (dry weight)	44.00±2.00
[%] organic C (dry weight)	24.46±0.54
[%] N (wet basis)	0.589±0.091
[%] N (dry weight)	1.87±0.04
[%] $NH_3 – N$	0.36±0.01
[%] P_2O_5 (dry weight)	1.45±0.07
[%] K_2O (dry weight)	1.79±0.06
[%] Ca (dry weight)	3.81±0.04
[%] Mg (dry weight)	0.78±0.03

Table 3. Microelements and heavy metals in aerobic stabilized sludge (mean ± standard deviation, n=3)

parameter	mg kg^{-1}(dry weight)
Fe	1590±23

Mn	490±7
Zn	130±8
Cu	40.0±0.5
Ni	17.2±0.9
Cr	13.4±0.4
Hg	0.0821±0.012
Cd	1.182±0.1
Pb	24.7±0.9

The proportion of heavy metals in the sludge was below the permitted concentrations for the sludge from WWTP which is supposed to be used in agriculture in Croatia [24]. The final compost was not analysed for heavy metals content based on determined heavy metals in the sludge. Many researchers have analysed the toxicity of heavy metals [25] and the migration of heavy metals in soil fertilized with sewage sludge [26]. In most European countries and many other countries, the heavy metals content in sludge used for agricultural purposes is limited [25], including Croatia [24]. The total concentration of heavy metals in sewage sludge cannot provide useful information about the risk of bioavailability, toxicity, and the capacity for immobilization in the environment. The mobility and bioavailability of heavy metals in soil fertilized with compost may change over time. During the process of composting of organic matter, humus substances can chelate heavy metals and reduce the bioavailability of these metals in the final product. The total content of metals in sewage sludge depends primarily on the source of wastewater (municipal, industrial) and their composition and less on the treatment of sewage sludge [27]. The results of the analysed sludge indicate that the sludge has valuable plant nutritional properties, with high amount of Ca, Fe and Mn, and can be used in agriculture. The sludge nutrient content, microelements and heavy metals were determined at University of Zagreb, Faculty of Agriculture. Moisture check was done by fist test [28]. Manual turning of the composting piles was performed once a week during the first month of composting, afterwards once a month.

Analytical methods

The eluent was prepared according to Huang *et al*. [13], and used for analysis. The compost pH was measured in deionized water extract (1:10 w/v) by WTWMulti 3420 SET KS1, Germany. The moisture content was measured by drying the material at 105 °C per 24 h and the ash content was determined by ignition at 550 °C per 5 h. Total nitrogen was determined by Kjeldahl method. Analysis of P_2O_5, K_2O, Ca and Mg was determined by atomic absorption spectroscopy (AAS). Heavy metals analysis was performed after acid digestion by AAS.

The 48-h germination assay was used for the test of the toxicity to plants [29]. For the determination of the seed germination index (GI), an aqueous extract was prepared. The test was conducted in the dark at 20±1 °C. A filter paper previously moistened with 8 mL of compost extract was placed in a 10 cm diameter Petri dish, with evenly placed 10 cucumber seeds. As a control, deionized water was used. For each compost three replicate were incubated. The GI was determined according to the formula (1):

$$GI\ [\%] = \frac{(treatment\ seed\ germination\ [\%]\ x\ treatment\ root\ length)\ x\ 100}{control\ seed\ germination\ [\%]\ x\ control\ root\ length} \quad (1)$$

RESULTS AND DISCUSSION

Sewage sludge is rich in organic matter, contains nitrogen, phosphorus, potassium and other nutrient elements, and might be used as a cheap source of organic substrate for aerobic composting. Sewage sludge has a high content of organic matter and a rich microbial community, which can decompose organic matter, and effectively solved the acidification problem caused by food waste during the process of composting. Co-composting can effectively shorten the entire composting cycle and improve the compost maturity and its fertilizer quality [30]. Also, co-composting of sludge and other organic waste was proven to be more effective than separate composting of waste, since it enhances many biogeochemical processes that are microbially mediated and lowers the loss of nutrients during composting [18]. Sewage sludge compost significantly improved the chemical and physical properties, such as nitrogen content, porosity, moisture, organic matter content and respiration, of the reclaimed soil in the landfill [31]. The sludge is characterized by low C/N ratio, high moisture content and thick structure [32]. Green waste as bulking agents provide free air space, They are fibrous carbonaceous material, and balance the water contents of composting mixture since they modify the properties of waste during composting such as low C/N ratio, high moisture, and high density of waste [33]. Food waste contain a great amount of organic matter which is easily degradable [11]. Food waste is characterised by low C/N ratio, high moisture, high concentration of nitrogen, and low pH value [14]. Food waste conversion efficiency and stability is quite low since the organic portion of food waste is unstable and readily acidified [34]. Fruit wastes are readily degraded to organic acids with high quantities of leachate, and therefore, mixing fruit waste with green waste (bulking agent) is highly recommended to obtain adequate moisture content for composting [35].

Variations of pH, temperature and moisture content in the composting piles during the three months of composting are shown in **Error! Reference source not found.**.

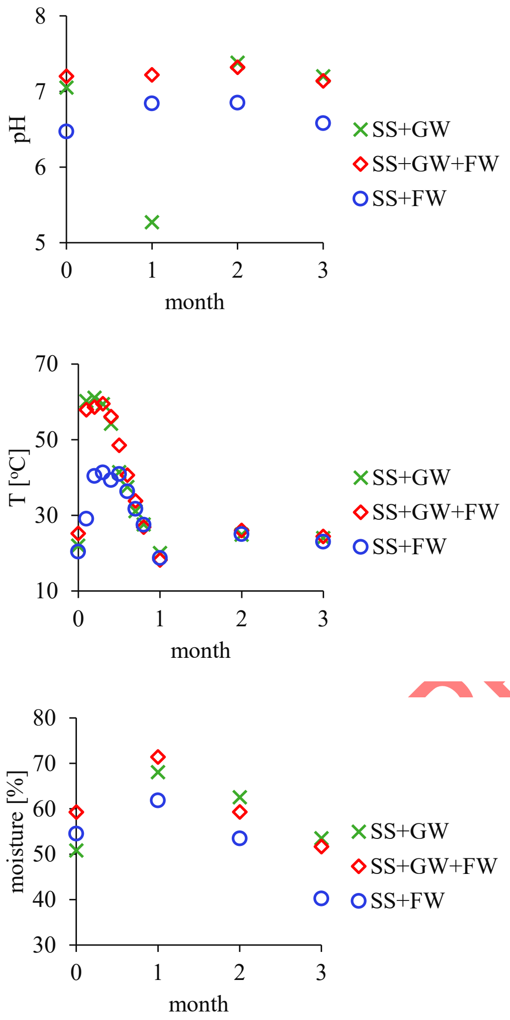

Figure 1. Variations of pH, temperature and moisture content in composting piles SS+GW, SS+GW+FW and SS+FW during 3 months

The variations of pH during the composting were the most intense in the mixture SS+GW. The acidification was observed with the lowest pH 5.27 recorded in the first month of composting. The composting in mixture SS+FW was performed under slight acidic conditions, with pH in the range 6.47-6.85. The final composts SS+GW, SS+GW+FW and SS+FW obtained pH of 7.20, 7.14 and 6.58, respectively (Table 1, **Error! Reference source not found.**), which is in the range of pH 6-8 for the mature compost [8]. During the composting of the mixture SS+GW+FW no acidification was recorded. Acidification during the food waste composting can be reduced by mixing food waste and sludge since sludge contains high organics concentration and numerous microbes capable of organics decomposition [30]. In early stage of composting, the acidic pH in composting mixtures is a result of organic degradation by acid-forming bacteria [35]. As the composting process continues, the ammonia is released due to ammonification and mineralization of organic nitrogen and pH becomes alkaline. In the final phase of composting, pH is around neutral due to formation of humus [9].

The temperature changes during the composting in composting mixtures SS+GW and SS+GW+FW exhibited a similar trend, with a slightly higher recorded temperature during the composting of the mixture SS+GW, while in the mixture SS+FW the temperature was lower. So, in this study the composition and moisture content of composting mixtures affected the temperature behaviour. Increasing temperature was recorded in the first week in all piles, in composting piles SS+GW and SS+GW+FW the observed temperature was above 55 °C, while in composting pile SS+FW the highest temperature was around 40 °C. After the initial temperature increase, a decrease was observed in all piles (Table 1, **Error! Reference source not found.**). In the study [30] of the co-composting of excess sludge and food waste (1:1, 2:1 and 4:1) and it was pointed out that the higher proportion of sludge, the higher the temperature, and vice-versa, and the highest temperatures recorded were 54.9ºC, 59.7ºC and 58.4 ºC in reactors containing 1:1, 2:1 and 4:1 sludge:food waste, respectively. Also, in study [18] it is suggested that the higher the C/N ratio, the higher temperature during the composting process, as well as in study [19], which is in accordance with results obtained in this study (Table 1, **Error! Reference source not found.**). The temperature transformations during the composting process can be identified as mesophilic, thermophilic, cooling and maturation [36]. During composting, in the first mesophilic stage, an increase of the temperature occurs as a result of the rapid mesophilic microorganisms' activity and colonization, which degrades organics and releases heat, which increases the temperature of the composting mixture. The heat speeds up the subsequent microorganisms' metabolism rate and in such a way decomposition of organics present in the composting mixture and the heat production. In the second, thermophilic stage, the temperature rises intensively, as a result of the high activity of microorganisms indicating the high degradation rates occurring during the mesophilic stage [37]. Then, in the third stage the temperature decreased significantly, as a result of the lower activity of the microorganisms due to the depletion of easily degradable organics [38]. The microflora diversity during the aerobic composting of biowaste (fruit and garden wastes, vegetable) was investigated [39]. As the composting process reached the thermophilic phase, the number of microorganisms declined, and raised as the temperature decreased. An enzyme activity assay, the indicator of overall microbial activity, exhibited the decline of microbial activity during the thermophilic phase, then increased, and eventually declined in maturation phase. The thermophilic phase was characterized by the predominance of bacteria (bacilli), with negligible amount of yeasts, streptomycetes and fungi. As the thermophilic phase was coming to the end, the variety of bacteria increased.

In this study, the measured temperature was suitable for growth of microorganisms, and in composting piles SS+GW and SS+GW+FW high enough for elimination of viable weed seeds and pathogens (hygienisation) [40]. For adequate hygienisation during at least 4 h over 55 °C all composting material should be exposed to [41]. Another study reported that after 96 days of home composting of leftovers of raw fruits and vegetables at average temperature 37.4 °C (variations between 20-65 °C) the produced compost was hygienised [40] due to natural decay of pathogens since the residence time of waste in home composting is relatively long [42]. Although during the composting process in this research the thermophilic temperature in composting pile SS+FW was not reached, since the composting was performed during three months, it is possible that the natural decay of pathogens occurred. The low C/N ratio of 8.75 in composting mixture SS+FW was the reason why the thermophilic conditions were not reached [11]. In experiments of co-composting of sewage sludge, straw and sawdust at C/N ratios 9.2, 12.1, 17.0 and 26.4 was highlighted that the ratio C/N significantly affects the temperature during the composting, in such a way that the higher C/N ratio, the higher the temperature and composting rate [19]. Furthermore, in experiments of co-composting of green waste and food waste at different C/N ratios and moisture content , at C/N ratio of 14.5 and moisture content 70.61% and 49.35% the highest recorded temperature was 35 ºC and 69.4 ºC, respectively [11]. It was pointed out that under high moisture content oxygen transfer limited the activity of the microorganisms which resulted in a slow temperature increase during the composting. Also, the microbial activity is directly affected by moisture content, and therefore so are temperature and decomposition rate. Contrary, it was pointed out that moisture content did not have significant effect on the compost quality [29] in experiments with pig feces and cornstalks at moisture content 65%, 70%, and 75%. Furthermore, it was highlighted that the temperature during the composting process is a case-specific parameter which does not explicitly depend on a composition of composting mixtures, it may also depend on other parameters [43].

The observed changes of moisture exhibited the same trend in all composting mixtures. The moisture variations showed the trend of the increase of moisture in the first month, and in the following months the moisture was decreasing. The final composts had the lower moisture content in composting mixtures SS+GW+FW and SS+FW. The moisture content loss was 7.62% and 14.31% in produced composts SS+GW+FW and SS+FW, respectively (**Error! Reference source not found.**). During the composting, the moisture content should vary 50 - 60% [2]. In some food wastes, such as vegetable waste, it can be more than 85% moisture content [18]. In this research, the moisture content varied depending on the composition of composting mixtures. The lower moisture content was recorded at the composting mixture SS+GW, 50.80%, since mixture SS+GW was composed of sludge and green waste, which is a bulking agent [5] and reduces the moisture content [44]. The sludge is often composted with bulking agents to reduce the thickness of sludge as well as the water content in the sludge. Another benefit of the addition of bulking agents to sludge is to provide aerobic conditions during composting [5]. The composting mixture SS+FW recorded the lowest moisture content in final compost, 40.19%. The final composts SS+GW and SS+GW+FW achieved very similar moisture content, 53.47% and 51.63%. Our results (Table 1, **Error! Reference source not found.**) are in agreement with the study. [6], in which was obtained moisture content in range 37.8-47.3% for final composts made of composting mixtures of sewage sludge, green waste and food waste, and with the study [30] in which was reported moisture content in range of 50.73-56.21% in co-composting of sludge and food waste.

The comparison of carbon and nitrogen proportion and C/N ratio in initial composting mixture piles with the final compost are shown in **Error! Reference source not found.**.

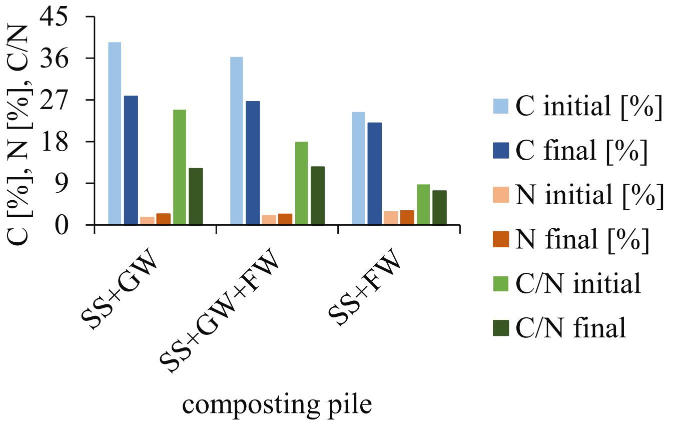

Figure 2. Carbon and nitrogen proportion and C/N ratio in initial composting piles and in compost in examined mixtures SS+GW, SS+GW+FW, and SS+FW

The carbon proportion in initial composting mixtures was as follows: mixture SS+FW (24.40%) < SS+GW+FW (36.26%) < SS+GW (39.45%). In spite of different starting points, the final composts SS+GW, SS+GW+FW and SS+FW obtained similar carbon proportions: 27.78%, 26.60% and 21.96%, respectively, with recorded carbon loss of 11.67%, 9.66% and 2.44%, respectively, expressed as the difference between initial and final value. The mass balance after 3 months of composting showed carbon loss of 29.58%, 26.64% and 10.00%, respectively, expressed as the ratio of initial carbon (**Error! Reference source not found.**). During the composting carbon transfer can happen among various organic fractions [45].

The mixtures SS+GW+FW and SS+FW contained higher concentration of nitrogen due to the addition of green vegetables (food waste) (Table 1), than the mixture SS+GW. Final composts SS+GW, SS+GW+FW and SS+FW in this research had 2.35%, 2.29% and 3.00% ratio of nitrogen, respectively, which is within values for good quality compost (0.4–3.5%) [46]. Nitrogen ratio in composts is an indicator of large fertilizing capacity and small loss of nitrogen due to emissions of ammonia during composting [40]. During the composting the conversion of unstable ammonia to stable, organic forms of nitrogen occurs [47]. The removal of NH_4-N from the compost is the result of nitrification. The nitrifying bacteria convert NH_4-N over nitrite to nitrate [48]. The final composts SS+GW, SS+GW+FW and SS+FW recorded a minor increase of nitrogen ratio, 0.77%, 0.28% and 0.21%, expressed as the difference between initial and final value. The mass balance after 3 months of composting showed nitrogen increase of 48.73%, 13.93% and 7.53%, respectively, expressed as the ratio of initial nitrogen (Table 1, **Error! Reference source not found.**). The loss of nitrogen occurs due to volatilisation during the composting process[49]. The reduced emissions of CO_2 and NH_3 are related to smaller loss of nitrogen, greater nitrogen amount [50] as well as organic carbon [51] in the final compost, which benefits the quality of compost [52]. Increase in nitrogen content in composting mixtures SS+GW, SS+GW+FW and SS+FW can be explained by the biodegradation of organics (decreased from 39.45% to 27.78% in mixture SS+GW, from 36.26% to 26.60% in mixture SS+GW+FW, and from 24.40% to 21.96% in mixture SS+FW, **Error! Reference source not found.**). The same was observed in study [21]. In composting process the nitrogen concentration increased because of a concentration effect due to the decomposition of the labile organics [53].

Initial C/N ratio of 25-30 is considered optimal for aerobic composting process [11], as well as 25-35 [12], however, the ratio C/N 15 [13], higher than 18 [14] and 20 [15] is also reported to be adequate for effective composting. The initial C/N ratios in composting mixtures increased in following order: SS+FW (8.75) < SS+GW+FW (18.00) < SS+GW (24.90)(**Error! Reference source not found.**). Other authors [18] also pointed out that the higher proportion of green waste, the higher ratio C/N, which is in accordance to the results obtained in our study. In this work the challenge in research was composting process at low C/N ratio (composting mixtures SS+GW+FW and SS+FW), and only the initial composting mixture SS+GW was set as recommended in the literature, in range 25-30 [11] or 25-35 [12]. In order to achieve conservation of nitrogen during composting, and to raise the availability of nitrogen in the final product it was suggested that the initial C/N ratio for sludge and bulking agents composting mixtures should be as high as possible [5]. Since bulking agents take part in carbon and nitrogen evolution, they affect and the characteristics of the final product and its agronomic value [20]. In another study was pointed out that when co-composting sludge, green waste and food waste (20-40% of sludge, 40-50% of green waste and 10-40% food waste), with an accent to optimal moisture content and C/N ratio, the greater contribution of sludge might decrease the C/N ratio [6], which is in agreement with our results.

The C/N ratios of final composts SS+GW and SS+GW+FW were quite similar, 12.12 and 12.49, respectively, while the C/N ratio of final compost SS+FW was the lowest, 7.30 (Table 1, **Error! Reference source not found.**). Regardless of different composition of initial composting mixtures and especially at low initial C/N ratio (8.75 and 18.00), all composts reached the C/N ratio as recommended in the literature (**Error! Reference source not found.**), around C/N 10 [54] or C/N 15 or lower [4], as an indicator of compost maturity. During the composting, organics are transformed to carbon dioxide, and with slightest loss of N, the ratio of C/N inevitably decreases [55]. The C/N ratio decreased in final composts SS+GW (51.3%), SS+GW+FW (30.6%) and SS+FW (16.6%) (**Error! Reference source not found.**). The decline of C/N ratio indicates mineralization during the composting [33]. Despite the fact that composting process emits more than 100 groups of gaseous compounds, the composting can be recognized as an environmentally friendly solution [56] and 99% of the total emission is made of CO_2, volatile organic compounds, NH_3, CH_4 and N_2O, and that emitted CO_2 is not derived from fossil and not regarded as an emission of greenhouse gas [57]. The composition of composting mixtures and the process parameters affects the amount and quality of emitted gases, and are substantially variable [58]. Sewage sludge composting and recycling can be an environment-friendly solution to disposal problems and an economic strategy for improving the soil conditions in landfills [31]. The benefits of the composting process are remarkable in terms of a valuable product production, reduction of waste – disposal of sludge, green and food waste, and is considered as eco-friendly process [58].

Mature and phytotoxic-free compost is compost with GI higher than 80% [59], which was achieved in this research (Table 4).

Table 4. Germination index of composts SS+GW, SS+GW+FW and SS+FW

Compost	Germination index [%]
SS+GW	85
SS+GW+FW	83
SS+FW	89

The high quality compost was obtained for all mixtures with final compost being dark-brown to black colour, with slightly more intense smell. The compost consistency was more balanced in the interior of the piles, with undecomposed woody material at the pile surface and the final compost should be sieved. Compost containing 2.6% nitrogen, 27% carbon, 0.9% phosphorus and 2% potassium can be considered as "high quality" compost [60].

The efficient recovery and reuse of sewage sludge and green waste and food waste make it environmentally safe and cost-effective solution of waste management [61]. Benefits of compost application in agricultural soils is maintaining or restoring the quality of soils, reducing the need for inorganic fertilisers, with a net contribution to the end-of-waste policy in Europe [62].

CONCLUSIONS

The co-composting of sewage sludge, green waste and food waste even at low C/N ratio of 8.75, 18.00, and 24.90 resulted in high quality compost and contributed to restoration and conservation of soil fertility, expanded the capability of carbon storage and decreased the use of synthetic fertilisers.

All produced compost are appropriate for agriculture use: however, since the compost of sewage sludge and food waste obtained the highest germination index (89%), it would be the most appropriate one.

Resource recovery from sewage sludge and other organic wastes has become the new focus of waste and wastewater management, to develop sustainable processes in a circular economy approach. The management of sewage sludge and other organic wastes (green and food waste) through composting gives benefits like cost reduction, compost environmental effects as organic soil amendments contributing to the increase of soil organic matter content, and is an important strategy to comply with the Landfill Directive and the end-of-waste policy in Europe.

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NOMENCLATURE

Abbreviations

WWTP	Wastewater Treatment Plant
SS	Sewage Sludge
FW	Food Waste
GW	Green Waste
GI	Germination Index
AAS	Atomic Absorption Spectroscopy

REFERENCES

1. European Commission, "European Commission Green Paper On the management of bio-waste in the European Union," *Off. J. Eur. Union*, 2010.
2. G. Tchobanoglous, H. Theisen, and S. Vigil, *Integrated solid waste management: engineering principles and management issues*. McGraw-Hill, New York, 1993.
3. Council of the European Union, *Directive 1999/31/EC on the landfill of waste*. 1999.
4. C. G. Golueke, "Principles of biological resources recovery," *Biocycle*, vol. 22, pp. 36–40, 1981.
5. J. Doublet, C. Francou, M. Poitrenaud, and S. Houot, "Sewage sludge composting: Influence of initial mixtures on organic matter evolution and N availability in the final composts," *Waste Manag.*, vol. 30, pp. 1922–1930, 2010, https://doi.org/10.1016/j.wasman.2010.04.032.
6. M. Mortula, A. Ahmad, and S. A. Shah, "Assessment of Mixing Potential of Sewage Sludge, Green Waste and Food Waste for Co-Composting in Sharjah, UAE," *Int. J. Environ. Sustain.*, vol. 5, no. 2, pp. 12–17, 2016, https://doi.org/10.24102/ijes.v5i2.670.
7. E. H. Tesfamariam, E. M. Malobane, C. G. Cogger, and I. Mbakwe, "The nitrogen fertilizer value of selected south african biosolids as affected by drying depth on beds," *J. Sustain. Dev. Energy, Water Environ. Syst.*, vol. 9, no. 2, p. 1080361, 2021, https://doi.org/10.13044/j.sdewes.d8.0361.
8. L. Cooperband, *The Art and Science of Composting A resource for farmers and compost producers*. Center for Integrated agricultural system, University of Wisconsin-Madison, Wisconsin, USA, 2002.
9. E. Epstein, *The Science of Composting*. Technomic Publishing Company, Inc., PA, USA, 1997.
10. R. T. Huag, *The practical handbook of compost engineering*. CRC Press, Taylor & Francis Group, USA, 1993.
11. M. Kumar, Y. L. Ou, and J. G. Lin, "Co-composting of green waste and food waste at low C/N ratio," *Waste Manag.*, vol. 30, pp. 602–609, 2010, https://doi.org/10.1016/j.wasman.2009.11.023.
12. P. Proietti, R. Calisti, G. Gigliotti, L. Nasini, L. Regni, and A. Marchini, "Composting optimization: Integrating cost analysis with the physical-chemical properties of materials to be composted," *J. Clean. Prod.*, vol. 137, pp. 1086–1099, 2016, https://doi.org/10.1016/j.jclepro.2016.07.158.
13. G. F. Huang, J. W. C. Wong, Q. T. Wu, and B. B. Nagar, "Effect of C/N on composting of pig manure with sawdust," *Waste Manag.*, vol. 24, pp. 805–813, 2004, https://doi.org/10.1016/j.wasman.2004.03.011.
14. E. R. Oviedo-Ocaña, I. Dominguez, D. Komilis, and A. Sánchez, "Co-composting of Green Waste Mixed with Unprocessed and Processed Food Waste: Influence on the Composting Process and Product Quality," *Waste and Biomass Valorization*, vol. 10, pp. 63–74, 2019, https://doi.org/10.1007/s12649-017-0047-2.
15. N. Zhu, "Effect of low initial C/N ratio on aerobic composting of swine manure with rice straw," *Bioresour. Technol.*, vol. 98, pp. 9–13, 2007, https://doi.org/10.1016/j.biortech.2005.12.003.

16. A. Malakahmad, N. B. Idrus, M. S. Abualqumboz, S. Yavari, and S. R. M. Kutty, "In-vessel co-composting of yard waste and food waste: an approach for sustainable waste management in Cameron Highlands, Malaysia," *Int. J. Recycl. Org. Waste Agric.*, vol. 6, pp. 149–157, 2017, https://doi.org/10.1007/s40093-017-0163-9.
17. F. Yang, G. X. Li, Q. Y. Yang, and W. H. Luo, "Effect of bulking agents on maturity and gaseous emissions during kitchen waste composting," *Chemosphere*, vol. 93, pp. 1393–1399, 2013, https://doi.org/10.1016/j.chemosphere.2013.07.002.
18. M. M. Mortula, A. Ahmed, K. P. Fattah, G. Zannerni, S. A. Shah, and A. M. Sharaby, "Sustainable management of organic wastes in sharjah, UAE through co-composting," *Methods Protoc.*, vol. 3, p. 76, 2020, https://doi.org/10.3390/mps3040076.
19. M. Neugebauer, P. Sołowiej, J. Piechocki, W. Czekała, and D. Janczak, "The influence of the C: N ratio on the composting rate," *Int. J. Smart Grid Clean Energy*, vol. 6, no. 1, pp. 54–60, 2017, https://doi.org/10.12720/sgce.6.1.54-60.
20. D. Rogeau, A. De Guardia, C. Druihe, and N. Le Mouel, "Role of bulking agent used for sludge composting: theoretical and practical considerations," in *ORBIT, Proceedings of the Third International Conference, Spain*, 2001, pp. 237–243.
21. S. Uçaroğlu and U. Alkan, "Composting of wastewater treatment sludge with different bulking agents," *J. Air Waste Manag. Assoc.*, vol. 66, no. 3, pp. 288–295, 2016, https://doi.org/10.1080/10962247.2015.1131205.
22. Z. Wang *et al.*, "Comparison of physicochemical parameters during the forced-aeration composting of sewage sludge and maize straw at different initial C/N ratios," *J. Air Waste Manag. Assoc.*, vol. 63, no. 10, pp. 1130–1136, 2013, https://doi.org/10.1080/10962247.2013.800616.
23. C. Tognetti, M. J. Mazzarino, and F. Laos, "Improving the quality of municipal organic waste compost," *Bioresour. Technol.*, vol. 98, pp. 1067–1076, 2007, https://doi.org/10.1016/j.biortech.2006.04.025.
24. OG 38/2008, *Ordinance on the management of sludge from wastewater treatment plants when sludge is used in agriculture*. https://narodne-novine.nn.hr/clanci/sluzbeni/2008_04_38_1307.html, 2008.
25. C. E. Gattullo, C. Mininni, A. Parente, F. F. Montesano, I. Allegretta, and R. Terzano, "Effects of municipal solid waste- and sewage sludge-compost-based growing media on the yield and heavy metal content of four lettuce cultivars," *Environ. Sci. Pollut. Res.*, vol. 24, pp. 25406–25415, 2017, https://doi.org/10.1007/s11356-017-0103-2.
26. B. M. Rajmund A, "The iron and manganese content changes in light soil fertilized with sewage sludge or composts during the 6– years lysimeter experiment.," *Water Env. Rural Areas*, vol. 1, no. 57, pp. 101–113, 2017.
27. M. Bożym and G. Siemiątkowski, "Characterization of composted sewage sludge during the maturation process: a pilot scale study," *Environ. Sci. Pollut. Res.*, vol. 25, pp. 34332–34342, 2018, https://doi.org/10.1007/s11356-018-3335-x.
28. The US Department of Agriculture and The US Composting Council, *Test methods for the examination of composting and compost*. Edaphos International, Houston, TX, The United States, 2001.
29. R. Guo *et al.*, "Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost," *Bioresour. Technol.*, vol. 112, pp. 171–178, 2012, https://doi.org/10.1016/j.biortech.2012.02.099.
30. R. Qin *et al.*, "Effect of excess sludge and food waste feeding ratio on the nutrient fractions, and bacterial and fungal community during aerobic co-composting," *Bioresour. Technol.*, vol. 320, p. 124339, 2021, https://doi.org/10.1016/j.biortech.2020.124339.
31. U. Song and E. J. Lee, "Environmental and economical assessment of sewage sludge compost application on soil and plants in a landfill," *Resour. Conserv. Recycl.*, vol. 54, no. 12, pp. 1109–1116, 2010, https://doi.org/10.1016/j.resconrec.2010.03.005.

32. M. P. Bernal, C. Paredes, M. A. Sánchez-Monedero, and J. Cegarra, "Maturity and stability parameters of composts prepared with a wide range of organic wastes," *Bioresour. Technol.*, vol. 63, pp. 91–99, 1998, https://doi.org/10.1016/S0960-8524(97)00084-9.
33. M. K. Iqbal, A. Nadeem, F. Sherazi, and R. A. Khan, "Optimization of process parameters for kitchen waste composting by response surface methodology," *Int. J. Environ. Sci. Technol.*, vol. 12, pp. 1759–1768, 2015, https://doi.org/10.1007/s13762-014-0543-x.
34. M. Kawai, N. Nagao, N. Tajima, C. Niwa, T. Matsuyama, and T. Toda, "The effect of the labile organic fraction in food waste and the substrate/inoculum ratio on anaerobic digestion for a reliable methane yield," *Bioresour. Technol.*, vol. 157, pp. 174–180, 2014, https://doi.org/10.1016/j.biortech.2014.01.018.
35. H. N. Chanakya, T. V. Ramachandra, M. Guruprasad, and V. Devi, "Micro-treatment options for components of organic fraction of MSW in residential areas," *Environ. Monit. Assess.*, vol. 135, pp. 129–139, 2007, https://doi.org/10.1007/s10661-007-9711-5.
36. K. Ishii, M. Fukui, and S. Takii, "Microbial succession during a composting process as evaluated by denaturing gradient gel electrophoresis analysis," *J. Appl. Microbiol.*, vol. 89, pp. 768–777, 2000, https://doi.org/10.1046/j.1365-2672.2000.01177.x.
37. C. Paredes, A. Roig, M. P. Bernal, M. A. Sánchez-Monedero, and J. Cegarra, "Evolution of organic matter and nitrogen during co-composting of olive mill wastewater with solid organic wastes," *Biol. Fertil. Soils*, vol. 32, pp. 222–227, 2000, https://doi.org/10.1007/s003740000239.
38. L. Zhang and X. Sun, "Influence of bulking agents on physical, chemical, and microbiological properties during the two-stage composting of green waste," *Waste Manag.*, vol. 48, pp. 115–126, 2016, https://doi.org/10.1016/j.wasman.2015.11.032.
39. J. Ryckeboer, J. Mergaert, J. Coosemans, K. Deprins, and J. Swings, "Microbiological aspects of biowaste during composting in a monitored compost bin," *J. Appl. Microbiol.*, vol. 94, pp. 127–137, 2003, https://doi.org/10.1046/j.1365-2672.2003.01800.x.
40. J. Colón *et al.*, "Environmental assessment of home composting," *Resour. Conserv. Recycl.*, vol. 54, pp. 893–904, 2010, https://doi.org/10.1016/j.resconrec.2010.01.008.
41. H. A. J. Hoitink and H. M. Keener, *Science and engineering of composting: design, environmental, microbiological and utilization aspects*. Worthington, Renaissance Publication, 1993.
42. S. Jasmin and S. Smith, *The practicability of home composting for the management of biodegradable domestic solid waste*. London: Centre for Environmental Control and Waste Management, Department of Civil and Environmental Engineering, 2003.
43. M. Himanen and K. Hänninen, "Composting of bio-waste, aerobic and anaerobic sludges - Effect of feedstock on the process and quality of compost," *Bioresour. Technol.*, vol. 102, pp. 2842–2852, 2011, https://doi.org/10.1016/j.biortech.2010.10.059.
44. M. Rihani, D. Malamis, B. Bihaoui, S. Etahiri, M. Loizidou, and O. Assobhei, "In-vessel treatment of urban primary sludge by aerobic composting," *Bioresour. Technol.*, vol. 101, pp. 5988–5995, 2010, https://doi.org/10.1016/j.biortech.2010.03.007.
45. M. H. Charest, H. Antoun, and C. J. Beauchamp, "Dynamics of water-soluble carbon substances and microbial populations during the composting of de-inking paper sludge," *Bioresour. Technol.*, vol. 91, pp. 53–67, 2004, https://doi.org/10.1016/S0960-8524(03)00155-X.
46. S. Sadeghi *et al.*, "Physical-Chemical Analysis and Comparison with Standards of the Compost Produced in Sanandaj, Iran," *OALibJ*, vol. 02, p. e1855, 2015, https://doi.org/10.4236/oalib.1101855.

47. N. Zhu, "Composting of high moisture content swine manure with corncob in a pilot-scale aerated static bin system," *Bioresour. Technol.*, vol. 97, pp. 1870–1875, 2006, https://doi.org/10.1016/j.biortech.2005.08.011.
48. M. K. Iqbal, T. Shafiq, A. Hussain, and K. Ahmed, "Effect of enrichment on chemical properties of MSW compost," *Bioresour. Technol.*, vol. 101, pp. 5969–5977, 2010, https://doi.org/10.1016/j.biortech.2010.02.105.
49. R. Parkinson, P. Gibbs, S. Burchett, and T. Misselbrook, "Effect of turning regime and seasonal weather conditions on nitrogen and phosphorus losses during aerobic composting of cattle manure," *Bioresour. Technol.*, vol. 91, pp. 171–178, 2004, https://doi.org/10.1016/S0960-8524(03)00174-3.
50. J. W. C. Wong, X. Wang, and A. Selvam, "Improving Compost Quality by Controlling Nitrogen Loss During Composting," in *Current Developments in Biotechnology and Bioengineering: Solid Waste Management*, Elsevier B.V., 2017, pp. 59–82.
51. "European Compost Network, ECN_NEWS. Organic resources and biological treatment, 2011, Siebert, S. End-of-waste criteria for Compost and Digestate." http://www.compostnetwork.info/wordpress/wpcontent/uploads/2011/05/ECN_EOW_Presentation-01_2011.pdf.
52. T. Hernández, C. Chocano, J. L. Moreno, and C. García, "Use of compost as an alternative to conventional inorganic fertilizers in intensive lettuce (Lactuca sativa L.) crops-Effects on soil and plant," *Soil Tillage Res.*, vol. 160, pp. 14–22, 2016, https://doi.org/10.1016/j.still.2016.02.005.
53. A. B. Morales, M. A. Bustamante, F. C. Marhuenda-Egea, R. Moral, M. Ros, and J. A. Pascual, "Agri-food sludge management using different co-composting strategies: Study of the added value of the composts obtained," *J. Clean. Prod.*, vol. 121, pp. 186–197, 2016, https://doi.org/10.1016/j.jclepro.2016.02.012.
54. B. Shaffer, *Curring compost; an antidote for thermal processing*, vol. 40, no. 11. Acres U.S.A., 2010.
55. M. Rasapoor, M. Adl, and B. Pourazizi, "Comparative evaluation of aeration methods for municipal solid waste composting from the perspective of resource management: A practical case study in Tehran, Iran," *J. Environ. Manage.*, vol. 184, pp. 528–534, 2016, https://doi.org/10.1016/j.jenvman.2016.10.029.
56. Y. C. Chung, "Evaluation of gas removal and bacterial community diversity in a biofilter developed to treat composting exhaust gases," *J. Hazard. Mater.*, vol. 144, pp. 377–385, 2007, https://doi.org/10.1016/j.jhazmat.2006.10.045.
57. F. Amlinger, S. Peyr, and C. Cuhls Carsten, "Green house gas emissions from composting and mechanical biological treatment," *Waste Manag. Res.*, vol. 26, pp. 47–60, 2008, https://doi.org/10.1177/0734242X07088432.
58. H. Y. Hwang, S. H. Kim, M. S. Kim, S. J. Park, and C. H. Lee, "Co-composting of chicken manure with organic wastes: characterization of gases emissions and compost quality," *Appl. Biol. Chem.*, vol. 63, no. 3, 2020, https://doi.org/10.1186/s13765-019-0483-8.
59. S. M. Tiquia and N. F. Y. Tam, "Elimination of phytotoxicity during co-composting of spent pig-manure sawdust litter and pig sludge," *Bioresour. Technol.*, vol. 65, pp. 43–49, 1998, https://doi.org/10.1016/S0960-8524(98)00024-8.
60. G. Ragan, *Project–Technology Research and Innovation Section, Compost*. Agricultural Technology centre. Virginia, 2002.
61. P. Alvarenga *et al.*, "Sewage sludge, compost and other representative organic wastes as agricultural soil amendments: Benefits versus limiting factors," *Waste Manag.*, vol. 40, no. 276, pp. 44–52, 2015, https://doi.org/10.1016/j.wasman.2015.01.027.
62. T. Turlej and M. Banas, "Sustainable management of sewage sludge," *E3S Web Conf.*, vol. 49, pp. 1–8, 2018, https://doi.org/10.1051/e3sconf/20184900120.