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Toward a Circular Bioeconomy within Food Waste Valorization: A Case Study of an On-Site Composting System of Restaurant Organic Waste

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Abstract: In the present and projected context of an increasing worldwide demand for food, the intensification of climate change effects on agriculture, and the depletion and degradation of natural resources, global actions must be taken to assure future food security for all people. Improper practices along the food supply chain, from primary production to consumption, generate huge quantities of food waste. Building a circular bioeconomy that feeds recycled materials back into the economy and minimizes the loss of resources will be an important step in introducing the world's food system to a sustainable path. The present case study describes an enclosed on-site composting system for food waste, operated in real-life conditions. The composting equipment was installed for a restaurant with specific needs in November 2020, located near a shopping center in Bucharest, the capital city of Romania. The physical, chemical, and biological characteristics of the compost came from a mix of food waste from a retail restaurant and sawdust pellets used as absorbent material, and these were analyzed to monitor compost quality and establish valorization opportunities. Two different monitoring campaigns were developed and the biological parameters were analyzed. The second monitoring campaign indicated that the compost was contaminated with *Escherichia coli* and *Salmonella* spp. When handled correctly and according to instructions, the composting process eliminates pathogens that may be present in food waste, such as *Escherichia coli*, *Salmonella* spp., etc., resulting in a high-quality compost that can be valorized in agriculture such as fertilizer or soil improver. Our results demonstrated that even when maintaining the same composition of raw materials in the composter, the quality and properties of the compost are greatly influenced by its operating conditions. Quality management procedures must be enforced and procedures must be strictly followed for the compost to be considered compliant. Compost that does not meet the requirements according to the regulation in force is again subjected to composting. If, after repeating the operation, the compost is still noncompliant, it is declared nonrecyclable waste, and must follow the specific procedure for such waste.

Keywords: circular bioeconomy; food security; composting; food waste; in-vessel composter; fertilizers; soil improver

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1. Introduction

The world's population of 7.7 billion in mid-2019 is projected to increase to 9.7 billion by 2050 and to nearly 11 billion around 2100 [1]. The rise in the global population, coupled with other factors such as economic development, income growth, increased life expectancy, urbanization, etc., will lead to a growing global demand for food. It is estimated that agriculture in 2050 will need to produce almost 50% more food, feed, and biofuel than it did in 2012. In sub-Saharan Africa and south Asia, agricultural output would need to more than double by 2050 to meet the increased demand [2].

Although almost 690 million people (8.9% of the global population) were undernourished in 2019 [3], about one-third of the global edible food (1.3 metric billion tons) is wasted annually [4]. This situation reflects the inequality between waste practices and food poverty, which has significant social, economic, and environmental ramifications. Food waste is associated with substantial economic losses, exacerbates food insecurity, and increases pressures on climate, water, and land resources, contributing to natural resource depletion and environmental pollution [5]. The impact of total food waste on climate, acidification, and eutrophication contributes to about 15–16% of the environmental impact of the entire food value chain [6].

The coronavirus disease (COVID-19), which has rapidly spread around the world since late 2019, has had significant implications for food security, nutrition, and food systems, and has worsened humanitarian emergencies. The implementation of strict lockdown measures caused a major global economic slowdown and disrupted supply chains, with effects on food systems and people's food security and nutrition [7].

Additionally, the war that began in Ukraine on 24 February 2022 has significantly disrupted livelihoods during the agricultural growing season, through physical access constraints and damage to homes, productive assets, agricultural land, roads, and other civilian infrastructure. The war has resulted in a massive food security challenge [8].

Along the food supply chain, from primary production to consumption, food waste reduction is a priority at the global and European Union (EU) levels. The United Nations defined the Sustainable Development Goals (SDG) in 2015 as a global call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030. Goal 12 of the SDG states: "Ensure sustainable consumption and production patterns." Amongst its objectives is target 12.3, referring to food waste: "By 2030, to halve per capita global food waste at the retail and consumer level, and reduce food losses along production and supply chains, including post-harvest losses" [9]. To achieve the SDG 12.3 target, the European Commission amended the Waste Framework Directive 2008/98/EC, making the monitoring and reporting of food waste mandatory in the Member States. Moreover, the European Commission has identified food waste as one of the priority areas of the European Circular Economy Action Plan for a cleaner and more competitive continent. This plan presents a set of actions to be implemented in Europe to facilitate and promote the transition to a more circular economy; the objective is to feed materials back into the economy and to avoid waste being sent to landfills or incinerated, thereby maximizing the value of the materials and reducing losses.

While the reductions in food loss and waste appear to be clear and desirable objectives, the actual implementation of this is not simple, and complete elimination may be unrealistic [10]. The food waste that is not reduced can instead be valorized by biological treatment methods such as composting and anaerobic digestion.

Composting represents the most widespread biological treatment method in the European Union. Composting of food waste plays an important role in the transition to a circular economy by reducing the volume of waste that would be deposited, promoting recycling, saving primary resources, and promoting recovery in agriculture from the final product (i.e., compost) [11].

Community composting is considered a sustainable way to manage the organic fraction of municipal solid waste and is a practice highly encouraged by the European Union [12]. There are several benefits of local composting, such as little to no cost for waste transportation and collection, low risk of pollution, more effective waste separation at the source, an increase in social awareness regarding organic waste recycling, and multiple uses for the resulting compost.

The sustainable use of compost in agriculture as a fertilizer or soil amendment means complying with the conditions necessary to obtain very good quality compost and the legislation on how it should be applied to soil, thus protecting the soil and the environment while reaping the beneficial effects of continuously using compost [11,13].

In Romania, the management of nonhazardous waste through composting is regulated through Romanian Law no. 181/2020 [14], which establishes the categories according to the CE marking criteria (Conformitè Europëenne (CE) Mark) and further uses of the resulting compost. In accordance with the draft of the technical norms that allow the implementation of this law, the separate collection of waste to be composted is mandatory. Depending on compost quality, the possible uses are as follows:

- *High-quality compost* (category I) used as flower soil, in homes, gardens, or vegetable gardens;
- *Very good quality compost* (category II) used for improving the properties of agricultural lands;
- *Good quality compost* (category III) used as an amendment for degraded soils;
- *Low-quality compost* (category IV) used only to cover landfills or ash dumps.

Law 181/2020 is the Romanian law on the management of compostable nonhazardous waste. The current law includes the basic principles transferred from Regulation (EU) 2019/1009 of the European Parliament and of the Council, from 5 June 2019, to lay down rules on the distribution of EU fertilizing products and amending Regulations (EC) No. 1069/2009 and (EC) No. 1107/2009 and repealing Regulation (EC) No. 2003/2003.

Regarding the quality of compost—in addition to its physico-chemical characteristics (such as nutrients, microelements, pH, and conductivity), the presence of beneficial microorganisms, and the absence of pathogens—an important factor that determines compost quality is the degree of loading with heavy metals and organic pollutants.

Heavy metals at high concentrations affect soil microbial populations, and these activities directly affect soil fertility [15]. High concentrations of heavy metals in agricultural soil can generate toxic effects on human health, and this negative effect is aggravated by the accumulation of heavy metals in the body over time, which can cause chronic intoxication [16].

Organic pollutants, such as polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), persist in the environment and have a negative impact on the environment and human health, expressed in the loss of biological diversity, development of carcinogenic diseases of the reproductive system, and nervous and immune system modifications [15,17]. An efficient technique for processing organic waste to obtain compost is thermophilic composting in enclosed systems [18].

The current study was conducted to investigate composting methods using on-site enclosed composting equipment for food waste, operated according to a technical protocol for proper management of the facility. Compost quality and its valorization opportunities were analyzed based on physical, chemical, and biological indicators.

2. Materials and Methods

2.1. Experimental Setup

In our experiment, we used an in-vessel automated composter. The composting equipment was installed near a shopping center with several restaurants in Bucharest, the capital city of Romania. The installation and commissioning of the composting equipment took place in November 2020. Trained personnel ensured the daily operations of the composting equipment, according to the established technical protocol.

The composter was designed for decomposing food waste in housing areas and restaurants, and has been sold in many countries since 1991. It consists of a container with a 2 m^3 volume and 392 × 108 (base) × 155 cm (height), equipped with a forced aeration system and a mechanical turning device. The aeration and turning are automatically performed, which means that the natural decomposition process perfectly works from start to finish. The average processing time of the machine is 6 to 10 weeks. All parts inside the composter that are in contact with the composted material are manufactured from stainless steel and the equipment is CE-marked.

The composter capacity is 40–70 kg food waste/day (25–42 tons food waste/year), depending on the food waste contents, moisture content, type of absorbent material, biological process, and how the machine is fed and programmed. From a technical point of view, food waste cannot be aerobically treated in the absence of structural material; thus, the food waste is fed into the composter together with 10–20 weight % of absorbent material. The biological process in the composter reduces the collected food waste by up to 90%.

Normally, there is no leachate from the equipment or the biological process. The composting process takes place in an in-vessel composting unit; thus, there are no unpleasant on-site odors.

Energy consumption is very low, even though the composting equipment is installed outside, because the cylinder is usually rotated for only 1 min every hour, and the biological process generates a temperature of 55–65 °C.

The container (vessel) system offers very good control of the composting process with many benefits for the environment.

2.2. Research Approach

For this study, the in-vessel composter was continuously fed with biological material represented by food waste from a retail restaurant, and sawdust pellets were used as an absorbent material.

To determine the quality of the compost and its valorization opportunities, monitoring campaigns were undertaken in 2021 and 2022. Compost was sampled according to the regulation in force for the identification of physical, chemical, and bacterial indicators. The sampling was carried out according to the standard EN 12579:2013 Soil improvers and growing media-Sampling [19]. These samples were prepared according to the standard EN 13040:2007 Soil improvers and growing media-Sample preparation for chemical and physical tests, determination of dry matter content, moisture content, and laboratory compacted bulk density [20]. The final sample size was 15 L for physical and chemical analysis. For the biological content, the final sample size was 1 L. Incremental samples were taken from the material, ignoring material closer than 50 mm to any surface. The microbiological samples were transported such that the samples were not subject to extreme temperatures and to ensure the material's characteristics were unaltered at the time of the delivery to the testing laboratory. Each sample arrived at the laboratory in less than two hours after sampling. All the samples were labeled according to the standard EN 12579. All the standards that were used for the identification of the different parameters in the study, as well as the reference values for each parameter, are illustrated in Table 1.

The compost samples were analyzed by an external laboratory authorized and accredited according to national and international standards. The list of indicators that must be considered when evaluating the quality of compost to ensure the protection of the environment and the health of the population is provided by the proposal on the technical norms for the application of Romanian Law no. 181/2020, regarding the management of nonhazardous waste through composting. The test method used for the microbial analysis of bacterial culture was an internal standard of the external laboratory that performed the analyses: the Laboratory of Microbiology of the National Research and Development Institute for Industrial Ecology/ECOIND, Bucharest, Romania.

During the monitoring campaign of 2021, the in-vessel composter was operated in very good conditions, according to the technical protocol. At the beginning of 2022, because of some unexpected technical problems and the short-term incapacitation of the personnel responsible for the composter's operation, the technical protocol could not be followed. In this situation, the composter wasn't fed daily, and the remote-control mode was used to modify the following operation parameters:

- Reducing the number of rotations from 3 to 2 rotations;
- Reducing the interval in which the rotations were performed from 2 h to 1 h and 30 min;

- Reducing the unloading of compost in the equipment from level 4 to level 6 (1 being the "most frequent" unloading level and 10 being the "least frequent" unloading level).

The operating parameters were modified to maintain an optimal level of material inside the equipment and maintain adequate temperatures (at least 40 °C) so that the bacterial activity was not destroyed.

2.2.1. Input Material

In this study, the biological material subjected to composting was the food preparation waste from a retail restaurant. The amount of organic waste generated by the restaurant ranged from 70 to 130 kg/day (including weekends). This resulted in approx. 47,450 kg/year of organic waste, which, prior to this study, was transported to a landfill.

Improper material such as plastic, metals, or paper was very rare and separately collected. The organic waste was delivered daily to the composter situated 30 m from the restaurant by trained personnel.

The absorbent material used was sawdust pellets. The composter was continuously fed with biological material, the quantities of food waste and sawdust pellets being 50 and 7.5 kg, respectively.

Table 1. Physical and chemical indicators of compost sampled on 10 May 2021 (P1) and 1 February 2022 (P2).

No	Indicator	Value P1 Sample	Value P2 Sample	Value According to the Proposed Technical Norms of the Romanian Law 181/2020	Unit	Analytical Methods
1	Moisture	62.2	67.0	NA	%	SR EN 15934: 2013 [21]
2	Dry matter	37.8	33.0	NA	%	
3	Total nitrogen	1.12	1.49	>1	% d.m.	SR EN 16168: 2013 [22]
4	Kjeldahl nitrogen	1.03	1.47	NA	% d.m.	EN 13342: 2002 [23]
5	Ammonium	111	200	NA	mg N/kg d.m.	ISO 7150-1: 2001 [24]; EN13652: 2002 [25]
6	Nitrate	438	814	NA	mg N/kg d.m.	ISO 7890-3: 2000 [26]; EN 13652: 2002
7	Nitrite	307	6.55	NA	mg N/kg d.m.	EN 26777: 2002; EN 26777: 2002/C91: 2006 [27]; EN 13652: 2002
8	P_2O_5 (total)	1.269	1.09	>0.5	% d.m.	EN 15309: 2007 [28]
9	K_2O (total)	0.748	0.50	>0.5	% d.m.	EN 15309: 2007
10	CaO (total)	1.647	1.76	NA	% d.m.	EN 15309: 2007
11	MgO (total)	0.328	0.25	NA	% d.m.	EN 15309: 2007
11	Na_2O (total)	1.614	1.07	NA	% d.m.	EN 15309: 2007
12	Calcination loss (organic matter)	93.35	94.62	>25	% d.m.	EN 15935: 2013 [29]
13	Organic carbon	47.44	49.90	NA	% d.m.	EN 15936: 2013 [30]
14	Soluble salts	2.51	0.45	>4	% d.m.	STAS 7184/7-87 [31]
15	Bulk density	511	436	<900	kg/m^3	EN ISO 17828: 2016 [32]
16	pH at 22.8 °C	8.4	7.1	6.5–9.5	pH unit	EN 15933: 2013 [33]
17	Electrical conductivity	7320	7320	NA	µS/cm	ISO 11265 + A1:1998 [34]

2.2.2. Process Conditions

After the input material is placed in the inlet, the temperature rises to 55–65 °C and the thermophilic phase begins. The microorganisms act on the organic waste (containing carbon) and decompose it by aerobic respiration. The required oxygen is introduced with a forced aeration system and the organic waste is turned inside the composter.

Keeping all the material inside the machine for 6–10 weeks and handling it correctly according to the instructions ensure a safe-to-use compost without odors or pathogens.

2.2.3. Description of the Protocol for Proper Management of the Facility

The technical protocol specifies the information necessary for proper management of the facility to obtain a safe-to-use compost, according to specific legislation.

In general terms, the composter should be at a location that minimizes transportation of food waste and access by unauthorized people.

Trained personnel should ensure the installation, commissioning, and operation of the composting equipment.

There is a risk of infection from collecting food waste that varies from site to site. The variation is due to different sources of food waste, collection routines, the age of the collected food waste, and its level of contamination.

When handled correctly and according to the instructions, the composting process eliminates pathogens that may be present in food waste, such as *Salmonella, E. coli*, etc. To prevent pathogens from spreading from food waste to other areas within the workplace or to the finished compost, the protocol mentions that protective clothing and gloves should be used while feeding the food waste into the composter.

The biological process does not only depend on the equipment's proper function. The operating parameters of the composter, i.e., adding sawdust or wood pellets with the food waste, ensuring the correct C:N balance, the number of rotations, and the wait time are equally important. Even more important is the quality of food waste fed into the composter, which has a direct impact on the biological process. It is well-known that biological processes work much better with mixed food waste, whereas a high moisture content can slow down or even stop them. If food waste is sterilized using chemicals, pesticides, cold, heat, or ingredients that inhibit bacterial growth before being put into the composter, the biological process will not properly function, lowering the composting capacity.

3. Results and Discussions

The values of physical and chemical indicators for the compost sampled on 10 May 2021 (sample code-P1) and 1 February 2022 (sample code-P2), compared with the reference values from the proposed technical norms for the application of the Romanian Law 181/2020, are presented in Table 1.

Based on the physical and chemical parameter values, included in Table 1, the analyzed compost samples met the criteria mentioned in Romanian Law 181/2020. The total nitrogen (TN) is the sum of nitrate nitrogen (NO3-N), nitrite nitrogen (NO2-N), amine nitrogen (NH4-N), and organically bound nitrogen structure. Total nitrogen (TN) should not be confused with total Kjeldahl nitrogen (TKN), which is the sum of ammonia-nitrogen plus organically bound nitrogen but does not include nitrate-nitrogen or nitrite-nitrogen.

The moisture content was observed to be 62.2% and 67%, for the first and second samplings, respectively, at the end of composting process, which slightly exceeded the upper value of 60% recommended in the literature for finished compost (40–50%). This was due to the composition of the raw waste

The results for the bulk density shown that they were within the recommended range by Romanian law, less than 900 kg/m^3, in line with other authors' results [35].

Neutral pH values are optimal for the composting process. Based on the results, sample P1 had a slightly alkaline composition, but the pH values for the mature compost were also well within the range indicated by Romanian law and obtained by other authors for food waste composting [36–38].

Total nitrogen values complied with regulations, and organic carbon values are similar with results that have been reported by different researchers [37,39].

Values for nutrients in the end-product revealed that the finished compost was of very good quality.

The electrical conductivity of the end-product is not specified in the Romanian law, but it should be noted that the values obtained for the final compost were almost twice the limit and the results mentioned by other authors [35,40].

The compost can be only used if accompanied by a certificate of conformity, attesting the product's classification in one of the categories mentioned in the framework. The results obtained for the two compost samples, presented in Table 2, indicated a high-quality compost (category I) based on its concentrations of heavy metal. The chemical compounds that were analyzed in the compost samples were: arsenic, cadmium, chromium, copper, mercury, nickel, lead, and zinc.

Table 2. Heavy metal concentrations for compost sampled on 10 May 2021 (P1) and 1 February 2022 (P2) compared with the maximum limits allowed for each category.

No	Indicator	Value P1 Sample	Value P2 Sample	Value According to the Proposed Technical Norms of Romanian Law 181/2020				Unit
				Category I	Category II	Category III	Category IV	
1	Arsenic	1.19	0.77	10	10	10	15	mg/kg d.m.
2	Cadmium	0.269	0.52	0.7	1.30	2	3	mg/kg d.m.
3	Chromium	2.87	16.7	70	100	120	150	mg/kg d.m.
4	Copper	2.49	14.9	70	110	150	200	mg/kg d.m.
5	Mercury	0.05	0.3	0.4	1	2	2	mg/kg d.m.
6	Nickel	1.51	10.3	25	40	60	70	mg/kg d.m.
7	Lead	0.572	4.92	45	130	180	200	mg/kg d.m.
8	Zinc	14.5	59.8	200	400	600	800	mg/kg d.m.

The bacterial indicators for compost sampled on 10 May 2021 (P1) and 1 February 2022 (P2) are presented in Table 3. The samples were taken at different periods of time to verify whether there were a similarities in the physical and chemical parameter values. The second sample P2 was taken to underline the influence of temperature on the biological processes.

Table 3. Bacterial indicators of compost sampled on 10 May 2021 (P1) and 1 February 2022 (P2).

No	Indicator	Value P1 Sample	Value P2 Sample	Value According to the Proposed Technical Norms of Romanian Law 181/2020	Unit
1	*Escherichia coli*	0	<1	1000	Probable number/g d.m.
2	*Enterococcaceae*	0	-	1000	Probable number/g d.m.
3	*Salmonella* spp.	Not detected	Detected/58 g d.m.	Not detected	Detected/not detected/mass

Sample P2 was positive for *Escherichia coli* and *Salmonella* spp. This sample was taken after the short period of time when the composting parameters were changed. Changes in operational conditions slowed the composter's functioning during this time, and the regular operator was incapacitated, resulting in an incomplete destruction of pathogens.

According to the provisions of Romanian Law no. 181/2020, compost that does not meet the requirements is again subjected to composting. If, after repeating the operation, the compost is still noncompliant, it is declared no-recyclable waste and follows the specific procedures for such types of waste.

4. Conclusions

In this study, we showed that the local composting of food waste can be an efficient method of reducing organic waste collected from restaurants and circulating nutrients. When operated under optimal conditions, and according to procedures that have been established empirically during the last 30 years, this type of enclosed composting equipment reduces food waste by up to 90% and produces high-quality compost (category I) with a low heavy metals content, and free of odor and pathogens. However, the long-term operation of an on-site installation is subjected to inherent hazards of daily life. The modification of optimal parameters to compensate for technical problems or lack of trained personnel can result in a deficient operation of the composter, as evidenced by the second experiment of the current study. In these unpredictable situations, a low-quality compost can be obtained, contaminated with pathogens, which will either require a repetition of the entire composting cycle or will be declared nonrecyclable waste. Nevertheless, as shown in the first study, when quality management is followed, there are advantages that support a circular bio economy: no transport of food wastes, which means zero emissions and mature compost that can be used as an organic fertilizer for green areas in the parking lots of the beneficiary. There is no need to purchase chemical fertilizers and the quantity of water and energy needed is also reduced. Due to the higher density content of the compost, the water evaporation rate is reduced. From a social point of view, this method of composting works to create a greener and safer environment.

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