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From anaerobic to aerobic treatment: upcycling of digestate as a moisturizing agent for in-vessel composting process

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Abstract

In Tunisia, there are crucial challenges facing both urban and rural areas, the most prominent of which are the production of organic waste, the need for waste treatment, the demand for water and energy and the need for a circular economy. To this end, the study was designed to develop a technical concept on closed cycle 'biowaste to bioenergy' treating, basically food waste (FW) through combined biological processes. In this approach, the generated digestate from FW anaerobic reactors was used successfully as a moisturizing agent for FW in-vessel composting. Four types of digestate were examined to be used as moisturizing agent (MA). The selection of the appropriate MA was achieved based on technical criteria; moisture content (MC), C:N ratio and heavy metals concentrations. The findings showed that the digestate obtained from anaerobic co-digestion of food waste and wheat straw (D1) was the most efficient AD-effluent to be added. In terms of composting process performance, the thermophilic phase of the amended reactor (A1) lasted 16 days and reached higher temperatures of about 72 °C, while the unamended one (A1) was characterized by a thermophilic temperature of around 66 °C indicating that the end products were of a pathogen-free compost. When it comes to the physico-chemical factors examined demonstrating that the biological conditions were sufficiently developed. The findings showed overall decreasing profiles during the composting period for moisture, C:N ratio as well as nitrification index (NI). From the quality-point of view, it was found that heavy metal concentrations had lower limits than those values set by German standards. Moreover, all the compost samples appeared to be stable and classified as class IV and V end product.

Keywords: Biological treatment, Food waste, Digestate, Moisturizing agent, Compost, European standards, End product quality

Introduction

Urban solid waste management is one of the most pressing and serious environmental problems facing urban governments in developing countries. This challenge will become even more severe in the future given the trends of rapid urbanization and the growth in the urban population (Arafat et al. 2015; Ferronato and Torretta 2019).

Improper collection and disposal of waste poses a serious health risk to the population causing a clear environmental degradation in most cities of the developing world (Meylan et al. 2018). With increasing public pressure and environmental legislation, waste experts are being called in to develop more sustainable methods of dealing with municipal waste (Abbasi and Gajalakshmi 2015; Abu Hajar et al. 2020). One of the steps in improving the current situation of solid waste is to enhance resource recovery activities. Recycling of inorganic materials from municipal solid waste is often well developed by the activities of the informal sector (Aparcana 2017).

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However, the reuse of organic waste materials, which often contributes more than 50% of the total amount of waste, is still limited but has an interesting recovery (Ardolino et al. 2020). Combined approaches to reduce reliance on landfills as a method of disposal and biological treatment is increasingly becoming a standard requirement for the vast majority of biodegradable waste (Bhatia et al. 2018).

Among all management options for organic waste, composting is the most approved method (Ardhaoui et al. 2019). It is an effective strategy to divert solid waste (SW) from landfills and improve the heating value of feedstock in case of energy recovery (Carabassa et al. 2020). Previous studies confirmed that composting reduces the volume of organic materials by more than 30% (Awasthi et al. 2020) and converts waste into a hygienic and valuable product (Chaher et al. 2020b; ChenYu et al. 2018).

Availability and variety of raw input materials, less of prerequisites, ease of technology, simplicity of concept, the environment and socio-economic benefits create a great opportunity in Tunisia to produce compost from organic waste (Aydi, 2015; Mahjoub et al. 2020). However, the opportunity to use the different types of organic waste as compost requires scientific studies that endorse it to guide users concerning the aspects behind the better management of the composting operation. In conjunction with the quantitative and life cycle-based evaluations, a comprehensive technical–scientific view of bio-waste composting should also include increasing the currently limited knowledge of the process performance in terms of monitoring and controlling the crucial factors affecting the efficiency of the composting units (Asadu et al. 2019; Chaher et al. 2020a). In this context, moisture content (MC) is a critical factor in the composting process. The optimal MC for effective composting depends on the specific physico-chemical properties and biological features of the materials to be composted (Kim et al. 2016; Xu et al. 2020). However, the optimum MC required for biological activity during composting is between 50 and 60%; Chaher et al. 2020b; Hemidat et al. 2018).

Several studies confirmed that moisture content has a remarkable effect on the composting process (Al-Bataina et al. 2016; Barthod et al. 2018; Du et al. 2018; Tibu et al. 2019). It influences the oxygen uptake rate, free air space, microbial activity and the temperature of the process. During composting, the MC is vital for the distribution of soluble nutrients needed for the microbial metabolic activity (Fan et al.2019). According to Xu et al. (2020) loss of moisture during the composting process can be counted as a strong indication of the decomposition rate. Very low MC could cause early dehydration during composting and that may hinder the biological process and slow down microbial activity under the low moisture range (Franke-Whittle et al. 2014).

It is well known that compost production is a very water-consuming process, as ensuring the required level of moisture requires large quantities of water. Many studies have claimed that every ton of ready-made compost needs 1 m^3 of water, and this is a significant amount that should be taken into account when planning such projects, especially in countries that suffer from water scarcity (Bacenetti, 2020; ChenYu et al. 2018; Tibu et al. 2019. Tunisia is one of those countries; it is considered one of the countries in the world with the scarcest water resources (Abdulrahman 2018; Ardhaoui et al. 2019). Tunisia is a water-stressed country with per capita renewable water availability of 486 m^3—well below the average of 1200 m^3/capita for the Middle East and North Africa Region (MENA) regions (Jemai et al. 2013). Indeed, the rapidly increasing population began to use more water than the country could provide (Mahjoub et al. 2020).

Therefore, there is an urgent need to seek an alternative to conventional water resources to be used in aerobic composting to ensure the required level of moisture content for an efficient composting process. To reduce the use of conventional water resources during the composting treatment, the research work aims to exploit an unconventional one; digestate produced from food waste (FW) anaerobic digesters to feed FW aerobic digesters. This option might be of considerable value by providing high-acclimated microbial diversity as well as micro- and macro-nutrients to enhance the process performance and the end product quality. A further objective is to examine its effect on FW in-vessel composting treatment as a moisturizing agent (MA).

Overall concept

The research work was launched in the framework of "RenewValue project" aiming to optimize the exploitation of different types of biowastes: food waste (FW), wheat straw (WS) and cattle manure (CM). The overall concept followed in the project is illustrated in Fig. 1.

The study aimed to recover the AD-effluents derived from anaerobic digesters treating mainly food waste. To this end, the experimental work was fundamentally divided into two phases. During the first one, the input materials (FW, WS, CM) were subjected to anaerobic digestion (AD), while the second phase was assigned to examine the exploitation of the digestate residue; from a by-product of the anaerobic treatment to feedstock for aerobic process which is the main target of the current study.

In this approach, the different pre-sorted bio-waste materials were processed to digestate and compost. In the first place, organic waste was converted into biogas

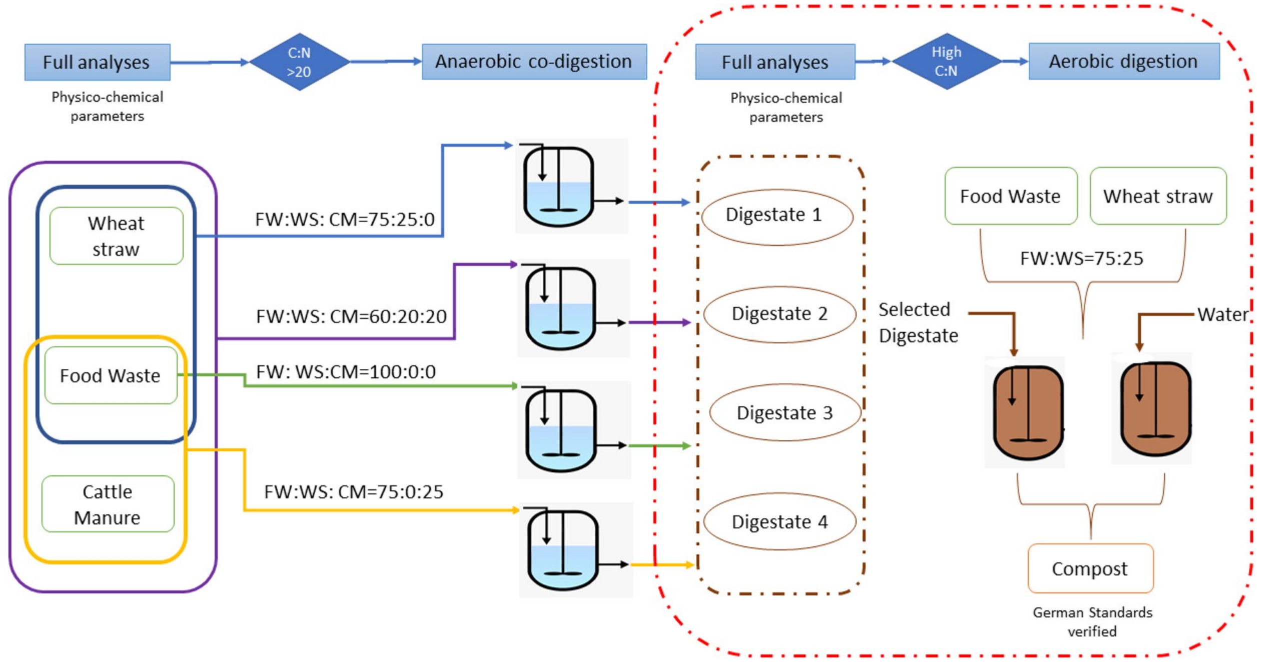

Fig. 1 Conceptualization of the overall "RenewValue" approach

and digestate. The latter was then exploited as a moisturizing agent (MA) for food waste and wheat straw in-vessel composting. Over the experimental work, the different organic residues were subjected to several processes such as conditioning, mixing, sampling and analysis.

Materials and methods

Anaerobic digestion

Different substrates-mixtures were prepared to feed, twice per day to feed eight (8) anaerobic reactors with a capacity of 20 L. Once the anaerobic treatment was accomplished, the generated digestates were collected to be fully characterized (Table 1). In addition, a comparison

Table 1 Physico-chemical characterization of the collected digestates

Parameters	Units	D1	D2	D3	D4	*D*$_1$ (Stoknes et al. 2016)
pH	–	7.49	7.51	7.02	8.13	–
Moisture content (MC)	% of FM	96.70	95.90	97.50	97.30	97.60
Carbon (C)	% of FM	37.60	35.20	40.10	37.20	–
Nitrogen (N)	% of FM	2.90	3.70	4.70	4.40	10
C:N ratio	–	12.97	9.51	8.53	8.45	–
Phosphors (P)	% of TS	3.02	3.17	2.87	2.91	1.00
Potassium (K)	% of TS	4.16	4.04	4.21	4.86	4.00
Lead (Pb)	mg/kg TS	2.33	2.46	2.29	2.54	0.43
Copper (Cu)	mg/kg TS	38.86	46.02	44.07	60.02	–
Zinc (Zn)	mg/kg TS	165.64	185.07	167.65	223.41	75.00
Nickel (Ni)	mg/kg TS	8.08	7.24	6.48	9.00	225
Cadmium (Cd)	mg/kg TS	0.32	0.40	0.35	0.38	8.94
Arsenic (As)	mg/kg TS	1.40	1.95	1.70	1.76	0.14
Mercury (Hg)	mg/kg TS	0.02	0.05	0.07	0.09	–

FM fresh matter, *TS* total solids, *D*$_1$ digestate collected from mesophilic anaerobic digesters treating FW (Stoknes et al. 2016) between the digestate properties examined during the current work and the results achieved by Stoknes et al. (2016) also treating food waste was performed.

Four types of digestates were generated and a detailed analysis was conducted for each; physico-chemical properties, macro- and micro-nutrients as well as the heavy metals contents were examined. Accordingly, selection criteria were developed. The latter were designed with regard to the main factors affecting the composting process performance as well as the end product quality. As a result, moisture content (MC) and C:N ratio were considered as steering parameters, while, in the second place, heavy metal (HMs) contents were given a lower priority as the four categories of digestates produced had HMs concentrations lower than the limits set by German Standards.

All the produced digestates met the technical specifications in terms of moisture content and HMs concentrations. However, the feedstock mixture prepared from FW:CM:WS = 75:25:0 and FW:CM:WS = 60:20:20, had a significant effect on the AD-liquid effluent characteristics. Indeed, digesters, including enriched nitrogenous components such as manure, were characterized by a lower C:N ratio, which is the case of D3 and D4. Moreover, the latter were influenced by the contribution of manure in terms of heavy metals (HMs); relatively high concentration compared to the rest.

Aerobic digestion

Raw materials

During the experimental work, FW was considered as the main substrate for the in-vessel composting process. FW was gathered from the canteen of the University of Rostock, Germany. It mostly consisted of pasta, salad, a small amount of meat and cooked potatoes. Once collected, it was conserved in small containers and stored at −20 °C to avoid any microbiological reaction. As a potential co-substrate, wheat straw (WS) was gathered from a farm in the vicinity of Rostock, after that the WS was chopped (< 10 mm) and stored in plastic airtight buckets kept at an ambient temperature. WS was selected to be added at a rate of 25% of the total fresh mass used referring to a previous research work (Chaher et al. 2020a). Further, mature compost (Mc) that was obtained from a local composting plant treating garden waste was used as a bulking agent (BA) to ensure the requested porosity and to sustain air spaces for oxygen transfer.

In addition to the oxygen supply, a performant aerobic treatment was ensured by a sufficient rate of moisture content (MC), an adjusted C:N ratio and an initial source of acclimated microorganisms. The amendment of composters with acclimatized digestate (D) aimed to save the amount of water to be added during the biodegradation of the organic materials and evaluate the effects of this on the process performance and the end product quality (Franke-Whittle et al. 2014).

Experimental setup

A 200-L laboratory-scale composter was used during the experimental work (Fig. 2). The composter is a stainless-steel vessel of a nominal inside diameter of around 700 mm and covered by a heat insulation layer to minimize heat losses. The airflow distribution is ensured by a metal grid with small holes fixed at the bottom of the vessel. The airflow was manually regulated during composting using a gas flow meter. Regarding the leachate collection, it was achieved by a fixed valve at the conical bottom of the composter. For the temperature monitoring, temperature sensors (TIR1) and (TIR2) were attached at different depths to monitor the fluctuation of the compost temperature. Both the compost temperature and the ambient temperature variations were automatically logged every 10 min using ALMEMO® data logger system (Ahlborn, German).

Two experimental trials were carried out to evaluate the impact of digestate addition on in-vessel FW composting. The composter was filled with around 55 kg of fresh matter. As a blank test, FW and WS co-composting without any amendment (A1) was firstly conducted in duplicate, then A2 was carried out to evaluate the digestate addition effects. Before feeding the composter, organic materials, including the bulking agent, were manually mixed and then the moisturizing agent (MA) was added. The moisture content of the initial starting material was adjusted to be in the requested range of 55–65% using water for the A1 test and digestate for A2. As the maintenance of MC at a certain range during

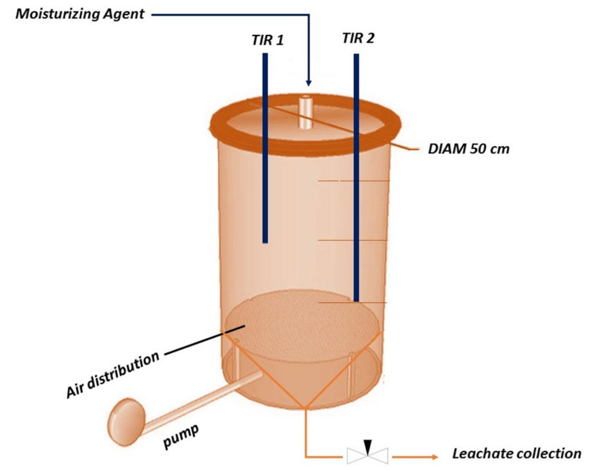

Fig. 2 Scheme of the in-vessel composter

the composting process is crucial, the amount of MA to be added (in litres) was determined to compare the consumption of digestate and water. Table 2 displays the trial ingredients and composting time.

Sampling and analysis

During the 9 weeks of the experimental work, sampling was achieved at regular intervals to evaluate the composting process evolution. Weekly, three representative samples were taken and were either analysed directly or stored (4 °C and -20 °C) for future analyses. Different parameters were determined in triplicate; moisture content (MC) (%), total carbon (TC), total nitrogen (TN), pH, electrical conductivity (EC), total solid (TS) (%) and mineral nitrogen content, such as ammonium (NH_4^+) and nitrate (NO_3^-), were monitored (Table 3). However, to follow-up the stability and maturity of the compost, respiration activity (AT_4) was identified at the end of the process. To assess the quality of the end product, heavy metals contents (HMs) were, in addition, measured to be compared to quality requirements for the compost of several countries with regard to Pb, Cu, Ni, Zn, Cd, Cr, Hg and As concentrations. All the experimental protocols carried out were described in detail in a previous work.

Table 2 Compost runs ingredients and duration of the process

Trials	Raw input material	Moisturizing agent	Initial weight (kg)	Duration (days)
A1	FW:WS	Water	54	36
A2	FW:WS	Digestate	56	36

Results and discussion

Physicochemical characteristics of the organic materials

The properties of the raw organic materials used are presented in Table 4. The moisture content was 77.4%, 6.5%, 53.3%, and 96.7% for FW, WS, Mc and D, respectively. To meet the required range of MC, which is 55–65%, a moisturizing agent (MA) was added to each mixture to regulate the MC of A1 to A2 at 65.8% and 68.7%, respectively. The initial C:N ratio was examined for each substrate to

Table 4 Physico-chemical characteristics of the raw materials

Parameters	Units	FW	WS	Mc	D
pH	–	4.22	–	7.80	7.49
Conductivity (EC)	(mS/cm)	5.71	–	3.29	–
Moisture content (MC)	% of FM	77.40	6.50	53.30	96.7
Total solids (TS)	% of FM	22.60	93.50	46.70	3.30
Carbon (C)	% of FM	47.7	47.63	22.50	37.60
Nitrogen (N)	% of FM	2.60	0.61	1.60	2.90
C:N ratio		18.35	78.08	14.06	12.97
Phosphors (P)	% of TS	0.48	0.06	0.52	3.02
Potassium (K)	% of TS	0.91	1.74	1.12	4.16
Magnesium (Mg)	% of TS	0.09	0.25	1.22	2.33
Lead (Pb)	mg/kg TS	0.91	0.21	20.63	38.86
Copper (Cu)	mg/kg TS	6.82	1.78	23.30	165.64
Zinc (Zn)	mg/kg TS	16.33	16.6	143	8.08
Nickel (Ni)	mg/kg TS	0.95	5.78	9.34	0.32
Cadmium (Cd)	mg/kg TS	0.07	0.08	0.26	1.40
Arsenic (As)	mg/kg TS	0.57	0.07	3.10	0.02
Mercury (Hg)	mg/kg TS	< 0.01	< 0.01	0.02	0.05

FM fresh matter, *TS* total solids

Table 3 Physical and chemical parameter measurement of composting parameters and their corresponding standard methods

Parameter	Frequency	Method	References
Moisture content (MC)	Each 5 days	Using electronic oven by drying at 105 °C for 24 h	NF ISO 11465 (1994)
Conductivity (EC)	Each 5 days	1:10 w/v sample: water extract	NF ISO 11265 (1995)
pH	Each 5 days		ISO 10390 (1994)
Total organic carbon (TOC)	Each 5 days	TOC (%) $= ((100 - \text{Ash }\%) \div 1/8)$	(Wang et al. 2018)
Total nitrogen (TN)	Each 5 days	Titrimetric methods	NF ISO 11265 (1995)
C:N ratio	Each 5 days	Expressed as ratio of (TOC/TKN) %	Wang et al. (2018)
NH_4^+	Each five days	1:5 w/v sample: water extract	NF ISO 11048
NO_3^-	Each 5 days	Ion chromatography	NF EN 10304-1
Nitrification index	Each 5 days	Expressed as ratio of (NH_4^+:NO_3^-)	Chaher et al. (2020a)
Total P and K	Start and end	Atomic absorption spectrometric methods	ISO 11885 (2007)
Respiration activity (AT_4)	At the end	CO_2 consumption by NaOH (1 N)	DIN ISO 16072
Heavy metals	At the end	Inductively coupled plasma-mass spectrometer, thermo-elemental ICP-MS-X series	ISO 11885 (2007)

ensure the required carbon to nitrogen rate demanded by microorganisms for an efficient biological degradation of the organics. Several studies reported that the appropriate initial C:N ratio of the feedstock ranged between 20 and 40 (Kumar et al. 2010; Tibu et al. 2019; Xu et al. 2020), which was achieved for both A1 and A2 to be around 33.28 and 31.07, respectively. Additionally, heavy metals and trace elements content were identified. Moreover, several physico-chemical characteristics, such as pH, conductivity (EC), potassium (K), phosphorus (P) as well as heavy metals, were investigated in order to guarantee an efficient development of the process.

Temperature monitoring profile during the composting process

Temperature is one of the most important factors governing the composting process. Therefore, the temperature evolution was monitored regularly to ensure efficient microbial activity and decomposition rate. As is evident from Fig. 3, which shows the temperature trends for different trials, three phases of the aerobic process were achieved (Torres-Climent et al. 2015). The modified reactor (A2) detected a rapid temperature rise during the second day, reaching 72 °C as the maximum temperature during the 16-day thermophilic phase. However, the A1 temperature profile was slightly different in terms of the highest temperature reached, as well as the duration of the thermophilic phase. The first temperature peak, which announced the onset of the thermophilic step, was recorded on day 5, while the second peak was marked with an ideal temperature of 66 °C on day 9 to drop to mesophilic temperature after 14 days. The thermophilic phase duration of both A1 and A2 met the criteria for obtaining pathogen-free compost according to BioAbfV (1998) which indicated that temperatures should be above 55 °C for at least 14 continuous days. Accordingly, the produced compost was considered hygienically acceptable.

By comparing temperature trends, the modified reactor accomplished the thermophilic phase faster with longer duration and higher temperature values which, in turn, emphasized the importance of adding digestate to the FW in-vessel composting process. Addition of AD-effluent had a significant effect in speeding up the heating of the composted material by providing an effective acclimatized inoculum. Similar findings were reported by Akyol et al. (2019) revealing that the fluctuation of temperature was a direct result of the enhanced microorganisms' activity. Therefore, the addition of a suitable microbial community served as a composting booster (Casini et al. 2019). Afterwards, the temperatures of the different trials decreased sharply, until a fixed set of values reached the ambient temperature, which announced the start of the cooling phase. Therefore, no significant degradation was achieved during the stabilization phase (from day 21 until the end of the process), while organic humification occurred at the same time (Li et al. 2017). The findings obtained are in line with several studies that confirmed the significant effect of adding digestate on temperature progression during the composting process (Al Seadi et al. 2013; Stoknes et al. 2016; Torres-Climent et al. 2015). However, assuming that the digestion

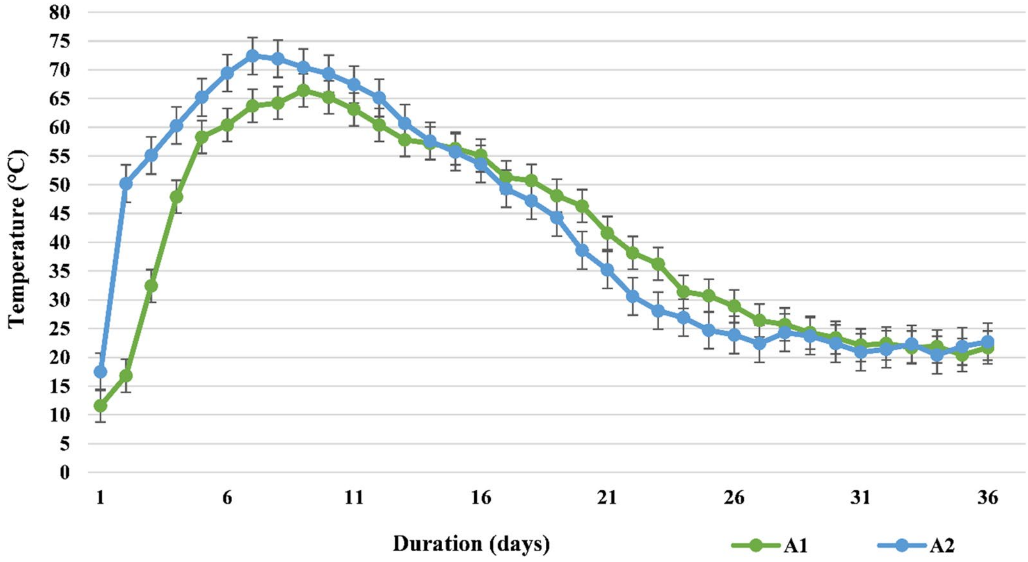

Fig. 3 Temperature profile during the composting process

acquired from AD reactors can be used directly as a soil conditioner, it was clear that pasteurization is mandatory to ensure its purification, which is the largest energy consumer in the anaerobic digestion (AD) chain (Liu et al. 2019). Therefore, during this research work, digestate exploitation was not only beneficial for improving composting performance but also for the AD energy saving approach.

Moisture monitoring profile during the composting process

Moisture content (MC) is one of the critical factors affecting the effectiveness of a biological treatment and must be monitored systematically over the period of the process and on a regular basis. (Zakarya et al. 2018). Since the digestate was characterized by a high MC of about 95.9%, the high water rate strongly guaranteed its sufficiency as an unconventional moisturizing agent (MA) for A2 (Kim et al. 2016). With regard to A1, the initial MC was modified by adding some amount of water to be within the required range of about 55–65%. The initial MC of A1 and A2 was titrated at 68.8% and 65.8%, respectively (Figs. 4, 5).

During the first two weeks, a significant decrease in MC occurred in A2, reaching 44%, while A1 had a water content of about 54.8% at the end of the thermophilic phase. In fact, the observed decrease in MC of modified reactors compared to the unmodified one was explained by the presence of an intense microbial community provided by the digestion, which then required a large rate of water and its consumption (Makan et al. 2013). Moreover, the abundance of microorganisms in A2 was clearly predictable from the temperature profile, and thus a measure of digestate was added to set the MC at around 50% (day 16). In terms of MA supplement, the volume of digestate added during the aerobic process was 1.2 times higher than the amount of water, ensuring an effective microbiological progress. Once the cooling phase occurred, the need for the addition of MA for different trials was not observed until the end of the treatment and a nearly stable moisture profile was recorded. At the end of composting trials, A1 and A2 were qualified by MC with 51.7% and 47.8%, respectively. The moisture trends were consistent with the findings from Arab and McCartney (2017) for examining the effects of digestate on physical and chemical parameters.

Effect of digestate addition on process stability and maturity

pH and C:N ratio

As the fluctuation of temperature and moisture influenced the organic matter degradability, pH behaviour was linked to their tendencies during the composting process. At the beginning of the process, the pH of both of A1 and A2 were nearly neutral at around 7.9. However, once the temperature rose, the pH behaviour of A1 was entirely opposed to A2 until the end of the thermophilic stage. Indeed, an acidic tendency was recorded for A1 which was due to the biodegradation of carbonaceous substances and then the emission of CO_2 causing an acidic pH (Kim et al. 2016). Contrary to A1, the matrix pH of the amended bioreactor A2 showed a progressive

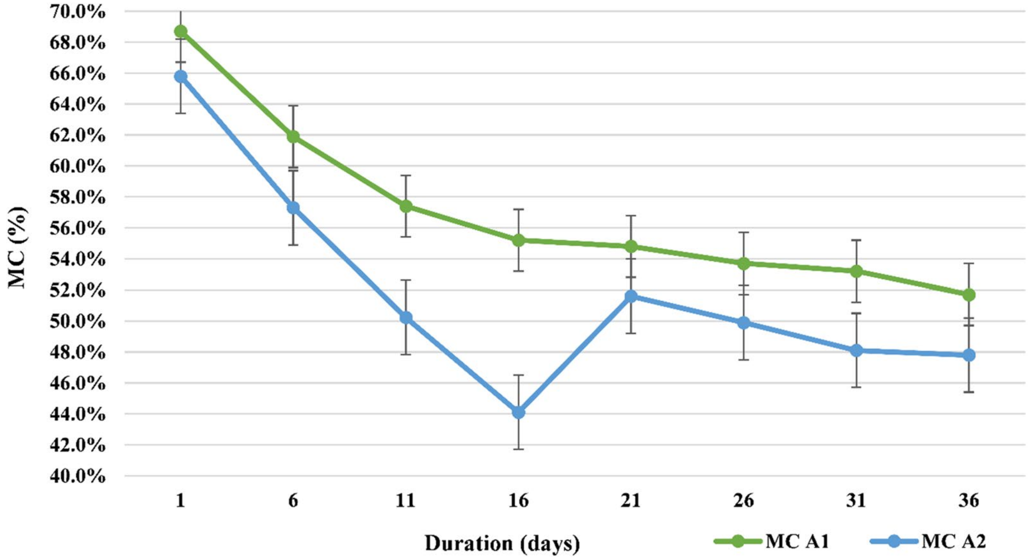

Fig. 4 Moisture content evolution during the composting process

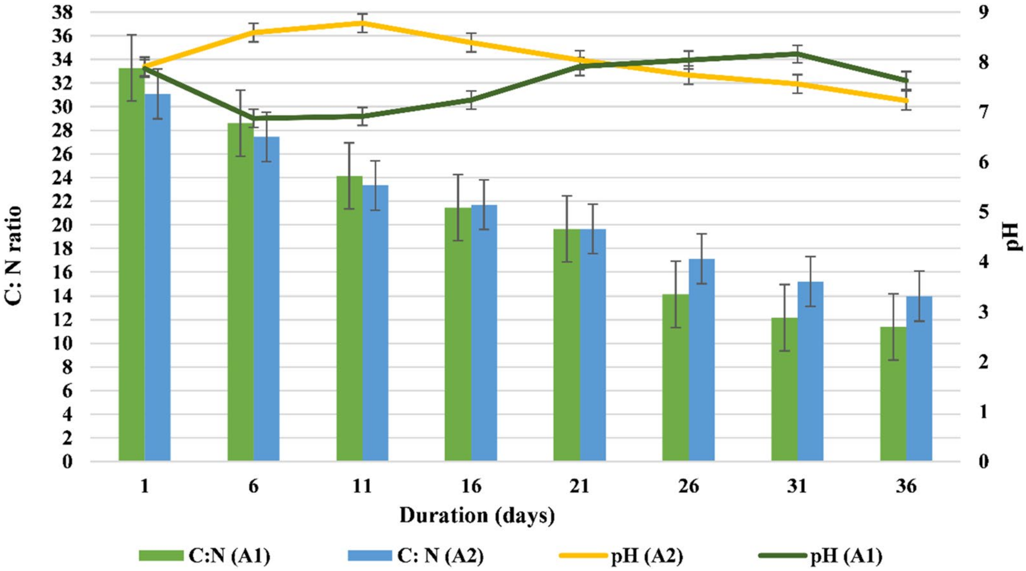

Fig. 5 C:N ratio and pH evolution during the composting process

increase from 7.91 to 8.59 during the first two weeks of the process and then decreased slightly to 8.39 at the end of the thermophilic phase. It was explained by the relatively high rate of nitrogen provided by the digestate and then an intensive volatilization of the nitrogenous elements (NH_3) which was followed by a peak of pH at high temperatures (Zakarya et al. 2018). The findings obtained were in line with several results investigating the effect of digestate on pH behaviour (Akyol et al. 2019; Arab and McCartney 2017). As the cooling phase progressed, pH values of both A1 and A2 dropped and generally stabilized between 8 and 7. These values were within the optimum range for growing media (Hemidat et al. 2018).

C:N ratio is one of the key monitoring factors during the composting process. It determines the level of the end product maturity and stability (Li et al. 2017). It was therefore monitored over the period of the composting process to follow-up the microbial activities of both of A1 and A2. The initial C:N ratio for A1 and A2 were around 33.28 and 31.07, respectively. Once the thermophilic phase began, the tendencies of the C:N ratio were almost the same for the amended and unamended reactors. Within the first few weeks, the C:N rate clearly decreased by around 36% for both A1 and A2 to reach 21.45 and 21.70, respectively. In fact, the drop of C:N ratio of the unamended reactor was a result of the decomposition of the easily degradable materials, while intensive losses in terms of nitrogen and carbon marked the amended vessels which was due to the abundance of the microbial community provided by the digestate decomposing the organic matter (Cáceres et al. 2018). Achieving the cooling stage, the C:N ratio of A1 seemed to be slightly stabilized compared to A2. It was attributed to the high rate of carbonaceous components consumption during the first five weeks and lower nitrification rate compared to A2 which was characterized by higher nitrogenous components. Since the carbon is assumed as a source of energy, while nitrogen is required for the growth of microorganisms, a balanced utilization of nitrogenous and carbonaceous elements marked the amended reactors to obtain higher C:N ratio during the cooling phase compared to the active one. However, both A1 and A2 reached C:N ratio of 11.38 and 13.99 which is in line with the previous studies revealing that the suitable final C:N ratio should be less than 20 (Chaher et al. 2020b; Hemidat et al. 2018).

Nitrification index (NI) and respiration activity (AT4)

Jointly with carbon, nitrogen is the major component in the aerobic digestion as it contributes to the microorganism's occurrence and, therefore, the main progress of the process. However, the nature of the treated biomass affects the amount of nitrogen available for the microbial community and then it influences the rate of nitrogen-conversion to ammonium (NH_4^+) and nitrate (NO_3^-) (Cáceres et al. 2016). As the ratio between NH_4^+ and NO_3^-; the nitrification index (NI) is considered as an indicator of the compost's stability (Chaher et al. 2020a), it was monitored during the composting process to evaluate the nitrogen transformation reactions. Figure 6 shows that, during the thermophilic phase, NI of the unamended reactor (A1) was considerably higher than

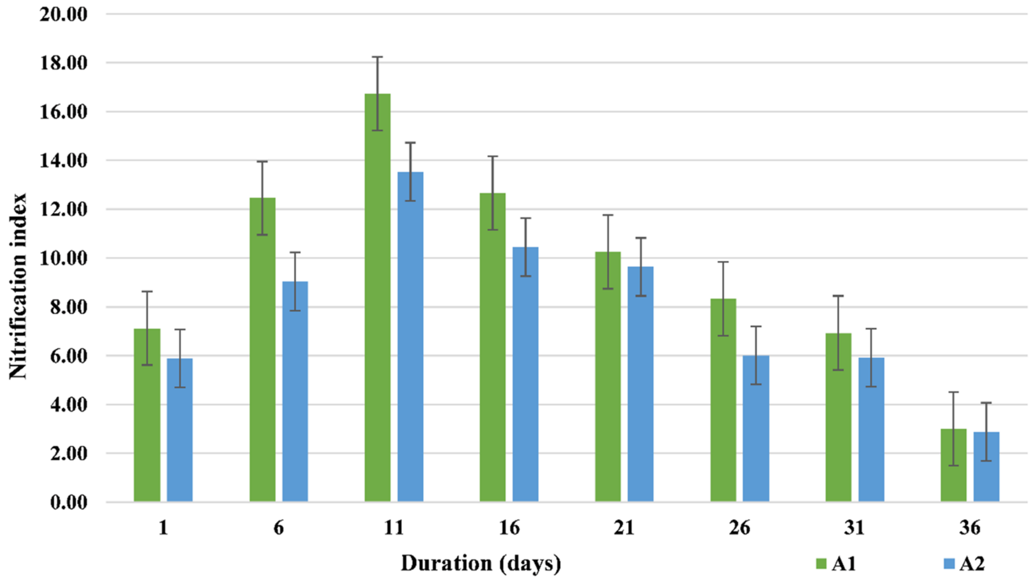

Fig. 6 Nitrification index tendencies during the composting process

the amended one (A2). It was seen that, for high temperatures (>40 °C), NI of A1 varied from 7.12 to 12.66, while it ranged between 5.89 and 10.44 for A2. The difference in terms of NI between A1 and A2 was due to the addition of digestate which is characterized by alkaline pH increasing NH_3 volatilization potential, declining the formation of NH_4^+ and raising the NO_3^- leaching (Markfoged et al. 2011). Several studies stated that, on average, a reduction of around 35–65% of the total nitrogen can be lost during the digestate composting, particularly if one of these factors existed; high pH (8–9), high temperatures (60%-70 °C) or high airflows in conformity with the current findings (Alburquerque et al. 2012; Sánchez-Rodríguez et al. 2018; Sangamithirai et al. 2015). Accomplishing the cooling phase, NI for both of A1 and A2 was progressively dropping to reach approximatively 3 at the end of the process. A nitrification index equal or lower than 3 indicated the maturity of the generated compost. Therefore, the end products produced from different trials were considered as finished compost at the end of the process period. Indeed, the significant decrease of NI, particularly for the amended reactor, was explained by the considerable oxidation of NH_4^+ to NO_3^- covered by specific groups of bacteria and archaea. The latter is one of the most abundant microorganisms characterizing the digestate as it is essential for the anaerobic degradation of the organic matter which justified the tendencies of NI in A2 compared to A1.

AT4 analysis was identified to assess the stability of the final products generated from both of amended and unamended bioreactors. All of the compost samples tested ascertained their stability with reference to German Standards (Table 5) and were considered to belong to class V.

Both A1 and A2 were characterized by low values of AT4, estimated to be 5.06 and 4.43, respectively, indicating that no more microbial activity will occur (Bazrafshan et al. 2016).

Effect of digestate addition on end product quality

Heavy metals' (HMs) measurement of the end products was based on the quality limits for agricultural use of several countries including Europe: Germany, UK, France as well as Canada and Tunisia. Table 5 summarizes the specification of seven HMs (Pb, Ni, Cu, Zn, Hg, Cr and Cd) for both of A1 and A2. It was notable that the rate of HMs for A2 was higher than for A1, especially for Zn which attained 80.20 for the unamended trial and 120.41 mg/kg TS for the amended one. Indeed, the significant amounts of metal components which marked A2 were predicted by the initial rate of HMs provided by the

Table 5 Classification of the compost samples according to German standards based on AT4 analysis

The class of compost	AT4 (mg O_2/g TS)	Product description
I	>40	Compost raw materials
II	28–40	Fresh compost
III	16–28	Fresh compost
IV	6–16	Finished compost
V	<6	Finished compost

Table 6 The limits of total metal content (mg/kg total solid (TS)) regarding the standards of certain countries

HMs	Samples		Standards						
	A1	A2	Tunisia	UK	France	EU	Canada	Germany	
								Class A	Class B
Lead (Pb)	11.93	14.40	180	200	180	120	150	150	100
Copper (Cu)	28.50	35.01	300	200	300	300	400	100	70
Zinc (Zn)	80.20	120.41	600	400	600	800	700	400	300
Nickel (Ni)	29.90	32.50	60	50	60	50	62	50	35
Cadmium (Cd)	0.26	1.41	3	1.5	3	1.5	3	1.5	1.0
Chromium (Cr)	57.49	81.30	–	100	120	100	210	100	70
Mercury (Hg)	0.01	0.04	2	–	–	1	–	1.0	0.7

digestate as described in Table 1. However, despite the remarkable content in terms of HMs, A2 met all the laws applicable in several countries and it was classified as a Class B biofertilizer in reference to the German Standards (Chaher et al. 2020a). Additionally, Table 4 shows that the compost gathered from A1 was categorized as Class A based on the German limits and illustrated that both amended and unamended reactors generated high qualified end products (Table 6). Admittedly, the main organic residues exploited were characterized by low rates of HMs which affirmed the outlined quality of the biofertilizer produced by the unamended composter but, initially, a slight uncertainty arose due to the addition of the AD-liquid effluent. Indeed, several works focused on the feasibility of the digestate recovery for agricultural benefits and highlighted that the inputs of AD-effluents in terms of HMs restricted its effectiveness (Stoknes et al. 2016).

Conclusion

The experimental research was designed to create a technical approach through the combination of the two major biological treatment technologies, anaerobic and aerobic digestion. A closed cycle 'biowaste to bioenergy' treating mainly food waste (FW) was examined. To this end, four types of digestate were collected from different anaerobic reactors to be exploited as moisturizing agents (MA) to feed FW and WS in-vessel composters. Moisture content (MC), C:N ratio and heavy metals concentrations were identified as the main steering factors for the selection of the appropriate MA. Results showed that the digestate obtained from the anaerobic co-digestion of food waste and wheat straw (D3) was the most suitable option; it was characterized by the most desirable C:N ratio of around 12, a good water content of 95.9% and a low rate in terms of heavy metals concentrations. The findings revealed that the in-vessel composting process was performed under ideal conditions. Focusing on the temperature tendencies, the duration of the thermophilic phase for both the amended reactor (A2) and the unamended one (A1) was sufficient to break down any kinds of pathogens threatening the quality of the end products. When it comes to the stability and maturity indicators, several physico-chemical properties were examined. The overall decreasing profiles during the composting period for moisture, C:N ratio as well as the nitrification index (NI) ascertained the efficiency of the AD-effluent addition to ensure a performant composting process. In addition, the respiration activity (AT4) indicated that no biological activity will take place as the compost generated from both of amended and unamended bioreactors were characterized by AT4 values lower than 6 mg O_2/g TS meeting the German Standards in terms of stability. Regarding the end product quality, German standards were also applied to verify the final HMs concentrations, A1 and A2 produced biofertilizers of class B and class A, respectively, proving the generation of high-quality composts. Therefore, the digestate was converted from an output hardly managed to an input comfortably recovered, reducing the consumption of a conventional water source and enhancing the composting process as an efficient source of acclimatized microorganisms.

Abbreviations

SW: Solid waste; MC: Moisture content; FW: Food waste; MA: Moisturizing agent; WS: Wheat straw; CM: Cattle manure; AD: Anaerobic digestion; FM: Fresh matter; TS: Total solids; D: Digestate; HMs: Heavy metals; TC: Total carbon; TN: Total nitrogen; EC: Electrical conductivity; NI: Nitrification index; AT4: Respiration activity.

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Authors' contributions

Conceptualization, NEHC; methodology, NEHC; formal analysis, NEHC, SH; investigation, NEHC, data curation, NEHC; writing—original draft preparation, NEHC; writing—review and editing, NEHC; supervision, AN, MC, MH and MN. All authors read and approved the final manuscript.

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Not applicable.

Consent for publication
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Competing interests
The authors declare no conflict of interest.

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