Upgrading of Food Waste in-vessel Composting Process: Effects of Biochar-rich Digestate Addition

Nour El houda Chaher (✉ nour.chaher@uni-rostock.de)
University of Rostock: Universitat Rostock *Department of Chemical and Process Engineering, National Engineering School of Gabes, University of Gabes, 6029 Gabes, Tunisia. https://orcid.org/0000-0002-2197-4491

Abdallah Nassour
Department of Waste and Resource Management, Faculty of Agrar and Environmental Sciences, University of Rostock, 18051 Rostock, Germany

Michael Nelles
Department of Waste and Resource Management, Faculty of Agrar and Environmental Sciences, University of Rostock, 18051 Rostock, Germany. *DBFZ German Biomass Research Center GmbH, 04347 Leipzig, Germany

Moktar Hamdi
Department of Biological and Chemical Engineering, National Institute of Applied Sciences and Technology, University of Carthage, 1080 Tunis, Tunisia

Research

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Abstract

Nowadays, Tunisia faces challenging environmental and energetic issues which concern mainly the implementation of an appropriate solid waste management system dealing with the high production of biowaste in one hand and the increased need for water and energy resources in the other hand. Therefore, the current study intended to develop a technical concept on closed cycle ‘biowaste to bioenergy’, treating mainly food waste (FW) through combined biological processes. In this approach, FW anaerobic digestion (AD) residue was destined to feed FW in vessel-composting as a valuable input material. To this end, the produced digestates from amended and unamended anaerobic reactors were entirely examined to select later the most appropriate AD-effluent. Therefore, the identification of the convenient digestate was achieved based on technical criteria; moisture content (MC), C : N ratio and heavy metals concentrations. The findings showed that the digestate obtained from different digesters was characterized by a high moisture content which inspired its utilization as an unconventional moisturizing agent (MA) reducing the fresh water consumption during the composting process. Because of the high C : N ratio, relatively significant rate of the needed macro and micro-nutrients, the exploitation of biochar-rich digestate was recommended to be used as an unconventional MA in one hand and an aerobic co-substrate booster in the other hand. Results showed that D3 addition promoted the composting process performance comparing to the blank test (A1). Indeed, the thermophilic phase of the amended reactor (A2) lasted 15 days and reached higher temperatures of about 67 °C, while the unamended one (A1) was characterized by a thermophilic temperature of around 63 °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.

1. Introduction

Inappropriate collection and disposal of bio-residues create serious concerns including environmental degradation, health risk to the citizens as well as socioeconomical problems which pose a strong instability, particularly in the developing world (Ferronato and Torretta 2019). The arisen public pressure and the evoked environmental legislation drove stakeholders, decision makers and experts to build stronger waste management strategies coping with the increased volume of organic waste (Guerrero et al. 2013; Marshall and Farahbakhsh 2013). In order to improve the existing solid waste system (SWS), it is crucial to upgrade the recovery conditions. Indeed, the recuperation of inorganic materials is frequently ensured by the informal sector ‘activity (Wilson et al. 2006), while a complete organization is mandatory to handle the high fraction of organic one. As this latter represented more than 50% of the total amount of waste in the developing countries, particularly in the Middle East and North Africa (MENA) region,
biowaste recovery was henceforth been assigned as a high-priority (Negm and Shareef 2020; Chaher et al. 2020c).

Tunisia, as a part of the MENA region, seeks to implement an efficient technic dealing with the significant volume of organic waste which was estimated to be around 68% of the total waste (Chaher et al. 2020b). Therefore, combined approaches are definitely needed to reduce in one hand the dependency on landfills and in the other hand take advantage of biowastes in efficient way (He et al. 2019). Indeed, the biological treatments are predominantly considered as a pattern for biodegradable residue treatment, then aerobic and anaerobic processes are often coupled as a dual technic to utilize different type of organic wastes (Bhatia et al. 2018). Moreover, the aforementioned benefits promote Tunisia to move towards combined biological treatments and produce simultaneously highly-qualified bioenergy and biofertilizer (Chaabane 2019; Chaher et al. 2020b).

Several studies confirmed that anaerobic and aerobic co-digestion were considered as an accomplishable option to treat organic residues, however it was also sometimes deemed to be of a limited performance (Sidélcio et al. 2017; Chaturvedi and Kaushal 2018; Lin et al. 2019). Hence, it is technologically challenging to build simple, sustainable and cost-effective option to maintain a stable anaerobic digestion (AD) systems and exploit efficiently the AD-effluents (Shen et al. 2016; Demichelis et al. 2019). With regard to AD stability, nowadays, a carbon-rich substrate addition such as biochar (Bc) attracted a special attention as it is characterized by physio-chemical properties dealing with the continuously evolving operational conditions (González et al. 2020). Even then referring to several studies working on Bc addition impacts on AD performance, Bc enhanced simultaneously AD-effluents quality: Biogas and digestate (Agegnehu et al. 2016; Agyarko-Mintah et al. 2017b; González et al. 2020). While, when it comes to the effectiveness of digestate' post-exploitation, it still remains limited. This latter was often utilized as a biofertilizer to be directly spread out to the land and its relevance as a soil improver as well as an efficient biofertilizer were substantially confirmed (Al Seadi et al. 2013; Stoknes et al. 2016). However, challenges associated to the appropriate management of AD-residue have risen, particularly with EU regulations on ammonia emission, high moisture content and heavy metals (Amery and Schoumans 2014). To overcome simultaneously the challenging issues, the post-treatment of biochar-rich digestate seems to be an attractive alternative combining pyrolysis and biological processes and interlinking biochar, digestate and compost which is the first aim of this research work.

In association with the life cycle-based estimation, a comprehensive technical-scientific evaluation of biowaste composting includes often limited skills regarding the process monitoring (Azim 2017; Xu et al. 2020). It is well-known that compost production is a significant water-consuming process, therefore moisture content (MC) is considered as a critical parameter which has to be usually under control (Zakarya et al. 2018). Therefore, for a sustainable biological activity, MC has to be in the range of 50% and 60% (Chaher et al. 2020b). Indeed, MC is one of the key factors which ensures the transfer of soluble nutrients needed for the microbial metabolic activity (Lee et al. 2004). Previous studies reported that water content has a significant effect on the composting process, as it influences the oxygen uptake rate, free air space, microbial activity and the temperature of the process ;(Makan et al. 2013; Kim et al. 2016;
According to Zakarya et al. (2018), a notable drop of water content is a substantial indicator of an efficient biodegradability, however a strong dehydration of the compost matrix may inhibit the aerobic process and hinder the microbial activity (Franke-Whittle et al. 2014). To this end, the retention of MC within the requested range and then the continuous wetting is essential, particularly during the thermophilic phase. Several studies affirmed that for one ton of finished compost, one cubic meter of fresh water is demanded (Hemidat et al. 2018; Fan et al. 2019). Therefore, this factor should be carefully crafted when planning such projects, especially in countries suffering from water shortage (Aboelnga et al. 2020; Scardigno 2020). As a part of those countries, Tunisia is classified as a water stressed country with per capita renewable water availability of 486 m³—well below the average of 1200 m³/capita for the MENA regions (Abdulrahman, 2018; Ardhaoui et al. 2019). Therefore, there is an urgent need to seek for an alternative replacing the conventional water resources which is the second target of this research work.

To sum-up, the present research work aims to seek for an alternative to reduce fresh water consumption, while ensuring the required level of MC in one hand and exploit efficiently biochar-rich digestate in the other hand. Hence, this substitution might be of a considerable interest by assessing amended AD-effluent as a valuable input boosting microorganism' activity and providing the required micro- and macro-nutrients to ensure a highly-qualified end-product.

2. Overall Concept

The research work was launched in the framework of « RenewValue project » aiming to boost the recovery of wasted food waste generated in Tunisia. The overall concept followed in the project was illustrated in Fig. 1. During the experimental work, FW was subjected of combined biological treatments: aerobic and anaerobic digestion. Therefore, the work was fundamentally divided into two phases. During the first one, FW was separately mixed with biochar (Bc) and agricultural residues such as wheat straw (WS) and cattle manure (CM) to feed anaerobic digesters, while the second phase was assigned to the upcycling of different AD residues.

In this approach, the collected digestates D1, D2 and D3 were entirely characterized to select the most appropriate one to be thereafter exploited as unconventional moisturizing agents (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.

3. Materials And Methods

3.1 Anaerobic digestion

3.1.1 From an output hardly managed to an input comfortably recovered
This work essentially aimed to take advantage of several types of co-substrates collected from different sectors of activity in order to enhance FW biological treatments. Therefore, aerobic and anaerobic digestion of food residues was carried out. However, during the biological experiments, two issues arose and then needed to be solved:

- With regard to aerobic process: A significant quantity of fresh water was needed to supply FW and WS in-vessel co-composting. Indeed, during the thermophilic phase, the water evaporation was significant which necessitated a continuous wetting of the bioreactors to keep a sustainable activity of the existent micro-organisms.
- With regard to anaerobic process: A significant quantity of digestate was generated which required storage, transport and treatment costs. However, the definition of agronomic value is very challenging, as there is not a specific quality-indicator of each AD-residue produced from different feedstock mixtures. Therefore, each digestate D1, D2 and D3 was entirely characterized to know how to deal with it.

Previous works emphasised the mechanical separation of AD-residue to take advantage of each fraction separately which was not applicable in the current case because of the high moisture contents of the generated digestates. Other studies focused on the exploitation of the digestates as a valuable source of nutrients to be rather extracted which is in one hand a high energy-consuming and in the other hand a pretty much sophisticated process. However, further researches pointed out the efficiency of digestates as a biofertilizer which can be applicable but under certain conditions. Table 1 summarised a comparison between the latter alternative effectiveness and the proposed combined biological treatments purposes.

### Table 1
Digestate upcycling processes: Conventional vs Unconventional technologies for digestate processing.

| Digestate (as an Unconventional Moisturizing Agent) | Digestate (as biofertilizer) |
|--------------------------------------------------|------------------------------|
| Digestates are produced continuously and can be also instantaneously exploited | Biofertilizers require an adequate storage to preserve their valuable nutrients |
| √ Cost of long-term storage are saved. | √ Appropriate conditions for a long-term storage of digestates are required. |
| Digestates can be biologically upcycled anytime needed : | Biofertilizers must be applied only during the growing season. |
| √ Efficient exploitation during the whole year. | √ Periodical use of digestates |
| √ Cost of further treatments is saved (dewatering, nutrient recovery...) | |
| Digestates sanitization is often required to destroy pathogens : | Digestate sanitization costs are saved. |
| √ The thermophilic phase of composting ensures the destruction of pathogens : Digestate sanitization costs are saved. | Biofertilizer quality has a direct impact on the generated crops quality and then on human health safety |
| | √ Digestates sanitization is required which is an energy consuming process. |
As the coupling of two processes when one of them is based on wet conditions and the subsequent one on dry conditions negatively affects the energy balance, a special attention was paid to combined biological treatments; aerobic and anaerobic digestion of FW (González et al. 2020). However, the selection of the most appropriate digestate was carried out basing on several criteria to ensure the effectiveness of the composting process and avoid the generation of a second non-recoverable residue.

### 3.1.2 Criteria for digestate selection

Different substrate-mixtures were prepared to feed, twice per day to feed six (6) anaerobic reactors with a capacity of 20 L. Once the anaerobic treatment was accomplished, the generated digestates were collected to be fully characterized. However, a comparison between the digestate properties were examined during the current work to check whether the gathered AD-residues dealt with the required physio-chemical criteria or not. In addition, the present results were compared to the achieved findings by Stoknes et al. (2016) which also achieved similar FW treatments. Table 2 summarized the physio-chemical characteristics of D1, D2 and D3 gathered from R1 (FW + WS + CM), R2 (100% FW) and R3 (FW + Bc), respectively. Therefore, several parameters were identified in order to determine suitable indicators to assess a potential agricultural use of digestates as well as the feasibility of their composting post-treatment. Accordingly, MC, pH, C:N ratio, and macro and micro-nutrients were examined.

As one of the steering factors, MC was firstly identified and a relatively high-water content of around 97% marked all the digesters. In practice, important moisture causes certain concerns such as odours, cost-intensive transport and hard storage facilities. Indeed, from there initially emerges the idea of using the digestates as unconventional moisturizing agents (Hosseini Koupai et al. 2019). However, as the generated AD-residues were characterized by almost the same water amount, further factors were fixed and served as pertinent selection criteria to well chose the most appropriate MA which will be introduced to the in-vessel composter. Starting with pH, it ranged around the neutral value for the unamended digesters (D1 and D2) which was beneficial for a direct digestate exploitation, while an alkaline pH of around 8.53 marked the amended one (D3). In fact, it was expected that the digester pH increased with the biochar addition because of alkaline nature of biochar sample (9.82) as well as the performance of this latter to organic matter removal (Sharma and Suthar 2020). Similar findings were reported by Shen et al. (2016) revealing that the derived biochar from woody substrates had a significant impact on the pH tendencies of the AD by-products. However, such a relatively high pH causes ammonium emissions whether is directly spread out to land which restricts its direct use and imposes an AD-residue post-treatment (Zakarya et al. 2018)(Örtl 2018). When it comes to C : N ratio, high value marked D3, while lower rates characterized D2 and D1, reaching 8.53 and 9.51, respectively. Indeed, both of FW and CM were initially rich in nitrogen which was converted by the microbial community into soluble forms and conserved in the digestates which explained the relatively low C :N of unameded reactors (Chaher et al. 2020b). However, the high carbonaceous content of biochar affected the carbon rate of the produced digestate from R3 to be around 47.60% of fresh matter (Casini et al. 2019). Additionally, the potassium concentration (K) of digestate harvested from biochar-amended digesters increased by 128% compared
to the control digester R2. This was mainly attributable to the cation release of the alkali metals (K, Ca and Mg) provided by the biochar (R3) and by the cattle manure (R1)

Table 2
Physico-chemical characterization of the collected digestates.

| Parameters                  | Units    | D1      | D2      | D3      | D1 (Stoknes et al. 2016) |
|-----------------------------|----------|---------|---------|---------|--------------------------|
| pH                          | -        | 7.67    | 7.79    | 8.53    | -                        |
| Conductivity (EC)           | mS/cm    | 5.23    | 6.12    | 11.72   |                          |
| Moisture content (MC)       | % of 1FM | 97.50   | 97.60   | 97.30   | 97.60                    |
| Crude ash                   | % of 2TS | 32.30   | 36.40   | 44.10   |                          |
| Carbon (C)                  | % of FM  | 40.10   | 35.20   | 47.60   | -                        |
| Nitrogen (N)                | % of FM  | 4.70    | 3.70    | 3.20    | 10                       |
| C:N ratio                   | -        | 8.53    | 9.51    | 14.88   | -                        |
| Phosphors (P)               | % of TS  | 3.87    | 4.17    | 4.91    | 1.00                     |
| Potassium (K)               | % of TS  | 5.21    | 5.04    | 11.86   | 4.00                     |

1 FM: Fresh Matter; 2 TS: Total Solids.

Further factors can be harmful to the environment. The pH level is important to determine innocuousness as it controls the behaviors of metals which are detrimental for soil (Al Seadi et al. 2013). Therefore, guidelines are usually established on total content of heavy metals. Table 5 shows the digestates’ characteristics in terms of heavy metals contents as well as some guidelines proposed by the European commission for digestates designed for agricultural use. Indeed, in order to sustain metabolic activity of the cell, some trace elements (TEs) such as Cd, Cu, Hg, Ni, Pb, As and Zn are required.
Table 3 illustrates that zinc (Zn) was the most abundantly trace element, followed by copper (Cu) and nickel (Ni). However, D1 and D3 were characterized by a relatively high rate of TEs, which was due to the initial contribution of the used substrates as well as the behavior of different co-substrates (manure and biochar), particularly in terms of Zn, Cu and Ni. A special attention was paid to cadmium (Cd), as it is relatively soluble on soils, readily consumed by crops, and then it is toxic to humans (Aydi 2015). However, the collected digestates were characterized by acceptable Cd concentrations, which were below the requested ranges. As the treated biomasses were initially characterized by low contents in terms of heavy metals, the examined digestates were also outlined by heavy metals concentrations below the limits imposed by the European Standards.

### 3.2 Aerobic digestion

#### 3.2.1. 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).

3.2.2. 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 minutes 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 56 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 the composting process is crucial, the amount of MA to be added (in liter) was determined to compare the consumption of digestate and water. Table 4 below displays the trial ingredients and composting time.

| Trials | Raw input material | Moisturizing Agent | Initial weight (kg) | Duration |
|--------|-------------------|-------------------|---------------------|----------|
| A1     | FW: WS            | Water             | 54                  | 37 days  |
| A2     | FW:WS             | Digestate         | 59                  | 37 days  |

3.2.3. Sampling and analysis

During the nine 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 (NH₄⁺) and nitrate (NO₃⁻), were
monitored. 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 regards to Pb, Cu, Ni, Zn, Cd, Cr, Hg and As concentrations. All the experimental protocols which were carried out were described in detail in a previous work (Table 5).

Table 5
Physical and chemical parameter measurement of composting parameters and their corresponding standard methods.

| Parameter                          | Frequency       | Method                                                                 | Reference                                |
|-----------------------------------|----------------|------------------------------------------------------------------------|------------------------------------------|
| Moisture Content (MC)             | Each five days | Using electronic oven by drying at 105°C for 24 hours.                 | NF ISO 11465 (1994)                      |
| Conductivity (EC)                 | Each five days | (1:10 w/v sample: water extract)                                       | NF ISO 11265 (1995)                      |
| pH                                | Each five days |                                                                        | ISO 10390 (1994)                         |
| Total Organic Carbon (TOC)        | Each five days | TOC (%) = ((100 - Ash %) ÷ 1/8)                                        | (Wang et al. 2018)                       |
| Total Nitrogen (TN)               | Each five days | titrimetric methods                                                    | NF ISO 11265 (1995)                      |
| C: N Ratio                        | Each five 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 five days | Ion chromatography                                                     | NF EN 10304-1                            |
| Nitrification index               | Each five 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)                         |

4. Results And Discussion

4.1. Physio-chemical properties of the raw materials
The characteristics of the exploited organic materials are illustrated in Table 6. 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 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 20–40 (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 physio-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.

Table 6
Physico-chemical characteristics of the raw materials.

| Parameters          | Units       | FW  | WS  | Mc  | D  |
|---------------------|-------------|-----|-----|-----|----|
| pH                  | -           | 4.22| -   | 7.80| 8.53|
| Conductivity (EC)   | (mS/cm)     | 5.71| -   | 3.29| 11.72|
| Moisture content (MC)| % of FM 1  | 77.40| 6.50| 53.30| 97.30|
| Total solids (TS)   | % of FM     | 22.60| 93.50| 46.70| 44.10|
| Carbon (C)          | % of FM     | 47.7 | 47.63| 22.50| 47.60|
| Nitrogen (N)        | % of FM     | 2.60 | 0.61 | 1.60 | 3.20 |
| C:N ratio           | -           | 18.35| 78.08| 14.06| 14.88|
| Phosphors (P)       | % of TS 2   | 0.48 | 0.06 | 0.52 | 4.91 |
| Potassium (K)       | % of TS     | 0.91 | 1.74 | 1.12 | 11.86|
| Lead (Pb)           | mg/kg TS    | 0.91 | 0.21 | 20.63| 4.33 |
| Copper (Cu)         | mg/kg TS    | 6.82 | 1.78 | 23.30| 76.32|
| Zinc (Zn)           | mg/kg TS    | 16.33| 16.6 | 143  | 285.07|
| Nickel (Ni)         | mg/kg TS    | 0.95 | 5.78 | 9.34 | 10.08|
| Cadmium (Cd)        | mg/kg TS    | 0.07 | 0.08 | 0.26 | 0.72 |
| Arsenic (As)        | mg/kg TS    | 0.57 | 0.07 | 3.10 | 2.32 |
| Mercury (Hg)        | mg/kg TS    | <0.01| <0.01| 0.02 | 0.02 |

1 FM: Fresh Matter; 2 TS: Total Solids.

4.2. Monitoring of steering parameters
4.2.1. Temperature profile during the composting process

Temperature is one of the critical parameters managing the aerobic digestion. Therefore, the temperature fluctuation was steadily controlled to guarantee an efficient control of biowaste degradation. Figure 3 illustrated the temperature fluctuation of amended and unamended trials. As reported by Torres-Climent et al., (2015), different phases of the composting process were successfully fulfilled. Starting with the thermophilic stage, the amended bioreactor (A2) showed a swift temperature rise attained in the third day, while the blank test achieved it after five days of the experimental setup. Indeed, for A1, the first temperature peak, which announced the onset of the thermophilic step was recorded on day 6, while higher temperature of 63 °C marked the digester on day 9 to drop to mesophilic temperature after 20 days. Whereas, the modified reactor reached faster the thermophilic phase (day 3) with a maximal temperature of around 70 °C. However, the thermophilic phase duration of the amended and unamended bioreactors met the criteria for obtaining pathogen-free compost according to BioAbfV (1998) which indicated that temperatures should be above 55 °C for at least for two successive weeks. Accordingly, the produced compost was considered hygienically acceptable.

Therefore, by comparing temperature trends, the modified reactor speeded up the thermophilic phase and expanded its duration (15 days) which emphasised the effectiveness of digestate addition. It might be also due to the influence the introduction of biochar to anaerobic reactors which played a crucial role to enhance the AD residue properties by intensifying the microbial activity (Chaher et al. 2020a). 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 stabilisation 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) as well as the effect of biochar on composting process improvement (Casini et al. 2019; Chaher et al. 2020a; Sharma and Suthar 2020). However, assuming that the digestion 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 as the attained temperature was sufficient to pasteurize the biological processes residues.

4.2.2. Moisture monitoring profile during the composting process

Moisture content (MC) is an important parameter governing the effectiveness of the composting process which has to be regularly determined over the experimental period (Xu et al. 2020). As a high MC of about 97% marked the digestate, it promoted its exploitation as an unconventional moisturizing agent (MA) (Kim et al., 2016). When it comes to the blank test, the adjustment of the initial MC, within the required
range of about 55% - 65%, was ensured by fresh-water addition which was not really practicable in Tunisia as a semi-arid country suffering from water scarcity. Figure 4 showed that the initial MC of A1 and A2 was titrated at around 65%.

During the first two weeks, a significant decrease in MC occurred in A1, reaching 51%, while A2 conserved a pretty much stable water content of about 55% at the end of the thermophilic phase. In fact, it was not expected that the amended trial maintained steady MC as the AD-residue was enriched by acclimatized microbial community and therefore a significant drop of MC was projected (Franke-Whittle et al. 2014). However, enhanced water capacity holding characterized A2 which was due to the biochar effects on moisture retention (Agegnehu et al. 2016). While, a considerable decrease in MC of the blank test affirmed that a large rate of water was consumed which required an extra need to fresh water addition (Makan et al., 2013). Indeed, in terms of MA supplement, the volume of the digestate one was 0.8 times lower than the volume of potable water used, ascertaining the effectiveness of unconventional moisturizing agent exploitation. Once the cooling phase occurred, the need for the addition of MA for different trials was not detected until the end of the treatment and nearly steady moisture tendencies were registered. At the end of composting trials, A1 and A2 were qualified by MC with 47.8% and 51.6%, respectively. The moisture trends were in line with the findings of Arab and McCartney (2017) examining the positive effect of digestate composting on aerobic process enhancement.

4.2.3. pH profile during the composting process

The organic matter degradability depends profoundly on the tendencies of the different steering parameters; temperature, moisture and pH which were to some extents interlined. Therefore, pH variations were periodically monitored. At the beginning of the process, the recorded pH values for both of the amended and unamended reactors were almost basic. Once the thermophilic phase began, pH profiles of A1 and A2 were almost the same, however pH values deviations were pretty much different. 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 (Chen et al. 2019). While, the modified digester A2 showed roughly a minor variance of pH ranging from 8.02 to 7.82 during the first two weeks of the composting process. It might be due to the potential of the biochar which was included in the anaerobic digesters on the alleviation of acid gas emissions (Casini et al. 2019; Chaher et al. 2020a). Indeed, the accomplished carbon sequestration ensured by the amended digestate was maintained until the end of the process to be around 8. Whereas, the compost which was generated from the blank trial was initially characterized by a quasi-acidic pH of around 6.82 and followed by a substantial rise of pH. In fact, it might be due to the significant content of nitrogen supplied by the used feedstock (FW) and therefore an intensive volatilization of the nitrogenous elements (NH$_3$) (Zakarya et al., 2018). The current results were in conformity with several results investigating the effect of digestate addition or rather biochar supplement on pH fluctuations (Al Seadi et al. 2013; Tibu et al. 2019). With the drop of temperature, pH values of both A1 and A2 stabilized between 8 – 7 which satisfied the required conditions in terms of pH values (Arab and McCartney 2017).

4.3. Monitoring of stability and maturity indicators
4.3.1. C : N ratio profile during the composting process

C: N ratio is known as one of the relevant key parameters that determines the status of maturity and stability of the generated compost (Li et al., 2017). It was therefore identified frequently to carry on the progress of the microbial community of different trials. The initial C:N ratio characterizing the modified and unmodified mixtures were around 32.21 and 29.74, respectively. Once the temperature rise, C:N ratio varied similarly for both of A1 and A2, however a significant drop of C: N values marked the blank test. Indeed, within the thermophilic stage, the C: N rate clearly decreased by around 43% to reach 18.36 which was due to the degradation of the rapidly consumable materials by the microorganisms entailing high losses in terms of nitrogen and carbon. When it comes to A2, the amended vessels presented lower C:N ratio fluctuations, then a quasi-stable C: N profile was shown in Fig. 6.

In fact, the revealed steadiness reflected a balanced degradation of carbonaceous as well as proteinaceous substances which was due to the abundance of the microbial community provided by the digestate in one hand (Cáceres et al., 2018) and the effect of biochar on ammonia and acid gases alleviation in the other hand (González et al. 2020). Accomplishing the cooling phase, the C:N ratio of A2 seemed to be slightly higher than A1. Therefore, it was attributed to the high rate of carbonaceous components consumption during the first five weeks as well as the lower nitrification rate which marked the blank trial. 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 12.78 and 14.51 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).

4.3.2. Nitrification index (NI) fluctuations during the composting process

Cooperatively with C:N ratio, the nitrification index (NI) which is the ratio between \( \text{NH}_4^+ \) and \( \text{NO}_3^- \) is well-thought-out as an indicator of the compost’s stability (Chaher et al., 2020a). Therefore, it was identified during the aerobic process to evaluate the nitrogen transformation progress. Nevertheless, the type of the exploited residues has a direct impact on the amount of nitrogen consumed by the present microorganisms and then it influences the nitrogen-ammonification in a first step and the nitrification rate later (Cáceres et al., 2016). Figure 7 illustrated that, for thermophilic temperatures (> 45 °C), NI of the blank test (A1) was significantly higher than the second trial (A2) rising from 7.12 to 12.66 for A1 and 5.89 to 10.44 for A2. Therefore, it was explained by the initial alkaline pH of the biochar-rich digestate used as well as its potential to enhance the nitrogen conversion (Agyarko-Mintah et al. 2017a). Indeed, the AD-residue promoted the formation of \( \text{NH}_4^+ \) and raising the \( \text{NO}_3^- \) leaching which leaded to a balanced NI compared to A1 (Markfoged et al., 2011). In addition, the considerable drop of NI which marked the amended trial might be due to the intensified number of bacteria and archaea essentially present in the digestate (Sánchez-Rodríguez et al., 2018). To this end, the specific microbial community is
one of the most crucial microorganisms ensuring firstly the anaerobic degradation of the organic matter and then boosting the oxidation of $\text{NH}_4^+$ to $\text{NO}_3^-$ during the aerobic process (de Jonge et al. 2020). Several researches reported that lower nitrogen losses occurred whether the digestate is composted which was in line with the current findings (Alburquerque et al., 2012; Sangamithirai et al., 2015).

Attaining the cooling phase, the amended and unamended bioreactors illustrated a progressive decline in terms of NI to be close of 3 at the end of the process. This letter indicated the maturity of the compost produced from both of A1 and A2 with reference to Örtl (2018).

### 4.3.3. Respiration activity (AT4)

The respiration activity (AT4) was also examined to evaluate the stability of the end-products generated from each bioreactor. Low values of AT4 marked both of A1 and A2 to be 4.06 and 3.43, respectively, and affirmed that no more biodegradation will occur (Bazrafshan et al. 2016). To this end, referring to German Standards (Table 7), the stability of all of the analysed compost samples were ascertained to be categorized as compost of class V.

### Table 7
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    |

### 4.4. Monitoring of end-product quality indicator : Heavy metals contents vs Compost Standards

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 8 summarized 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 digestate as described in Table 5. 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 A biofertilizer in reference to the German Standards (Chaher et al., 2020a). Additionally, Table 8 shows that the compost gathered from A1 was categorized as Class B based on the German limits and illustrated that both amended and unamended reactors generated high qualified end products. 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).

Table 8
The limits of total metal content (mg/kg total solid (TS)) regarding the standards of certain countries.

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

4.5. Evaluation of Biochar Effect on FW Composting

The above results showed that both of A1 and A2 produced stable, mature and highly-qualified composts with regard to several indicators, however a compost of Class B was generated from the amended FW in-vessel composter. Indeed, the effect of biochar-rich digestate addition influenced not only the biofertilizer characteristic but also the efficiency of the aerobic process performance. Table 9 summarized all the obtained results and compared the progress of A1 and A2.
Table 9
Characteristics of biofertilizers gathered from each bioreactor.

| Trial | Thermophilic Phase Duration (days) | $T_{\text{max}}$ (°C) | MC (%) | pH | NI | C: N Ratio | AT4 (mg $O_2$/g TS) | Classification vs. “German Standards” | Color |
|-------|------------------------------------|------------------------|--------|----|----|------------|----------------------|--------------------------------------|-------|
| A1    | 13 days                            | 63 °C                  | 47.8%  | 7.05 | 2.21 | 12.78      | 4.06                 | Class A                             | Brown |
| A2    | 15 days                            | 67 °C                  | 51.6%  | 8.06 | 2.61 | 14.51      | 3.43                 | Class B                             | Dark  |

5. 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. In order to enhance the anaerobic co-digestion of food waste, conventional co-substrates such as agricultural residues were added to be compared with the effects of an unconventional one; biochar. Once the anaerobic process was achieved, the exploitation of AD-residue was evaluated as an alternative to promote the aerobic treatment of FW. To this end, three kinds of digestate were gathered to be entirely analysed and then select the most appropriate one. Steering parameters such as moisture content, C:N ratio and macro and micro-nutrients were examined. Results showed that the digestate obtained from the amended anaerobic digester with biochar was the most suitable option; it was characterized by the most desirable C:N ratio, a good water content and an acceptable 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 physio-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

SWS: solid waste system

MENA: Middle East and North Africa
AD: anaerobic digestion
Bc: biochar
MC: moisture content
FW: food waste
WS: wheat straw
CM: cattle manure
D: digestate
MA: moisturizing agent
FM: fresh matter
TS: total solids
TES: trace elements
Mc: mature compost
BA: bulking agent
HMs: Heavy Metals contents
TC: Total Carbon
TN: Total Nitrogen
EC: Electrical Conductivity
NI: Nitrification Index
AT4: Respiration Activity

Declarations

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Ethics declarations
• Ethics approval and consent to participate

Not applicable.

• Consent for publication

Not applicable.

Availability of data and materials

All data generated or analysed during this study are included in this published article.

Conflict of interest

The authors declare no conflict of interest.

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Authors’ contributions

Conceptualization, N.E.H.C.; methodology, N.E.H.C.; formal analysis, N.E.H.C.; investigation, N.E.H.C., data curation, N.E.H.C.; writing—original draft preparation, N.E.H.C.; writing—review and editing, N.E.H.C.; supervision, A.N. , M.H. and M.N.

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Figures

Figure 1

Conceptualization of the overall « RenewValue » approach
Figure 2

Scheme of the In-Vessel composter.
Figure 3

Temperature profile during the composting process.
Figure 4

Moisture content evolution during the composting process.
Figure 5

pH evolution during the composting process.

Figure 6

C: N ratio fluctuations during the composting process.
Figure 7

Nitrification index tendencies during the composting process.

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