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Review

Suitability of Composting Process for the Disposal and Valorization of Brewer's Spent Grain

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Abstract: The brewing industry is characterized by the large production of by-products. Following the fundamentals of a circular economy, several attempts to recycle brewers' spent grain (BSG) have been investigated. However, little information is available on its use for composting. Considering the main parameters required for optimal development of composting, the objective of the present review was to analyze the literature to determine whether the microbial and physicochemical characteristics of BSG make it suitable for direct composting. As the main factors in the composting process, we considered the BSG moisture content, total carbon, total nitrogen, C/N ratio, and pH. As described in the literature, the BSG moisture content, C/N ratio, and pH range from 70.6% to 81.3%, 7.1 to 26.5, and 3.8 to 6.9, respectively. This C/N ratio range is lower than the composting target range (20–30). Instead, the mean moisture content in the literature is higher than the 60% to 65% recommended for composting. Optimum pH for aerobic stabilization of compost ranges from 5.5 to 7.5, while the BSG pH in the literature is typically more acidic. Therefore, BSG is not suitable for direct composting. Addition of lignocellulosic bulking agents improves the reduction of moisture content during composting, while also optimizing the substrate properties, such as C/N ratio, air spaces, and pH, to positively affect the composting process. Moreover, livestock manure should be included as a starting material to promote the composting process. In this context, two hypothetical initial mixtures of BSG plus a lignocellulosic bulking agent and livestock manure are presented.

Keywords: aerobic stabilization; agro-industry by-product; brewing industry; circular economy; organic fertilizer

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1. Introduction

The concept of a circular economy was developed to overcome the traditional linear economic model of "take, make, and dispose" [1]. This new business model focuses on sharing, re-use, repair, and recycling, as a closed loop. In a circular economy, two types of materials have been identified: biological and technical. The biological material can be decomposed by microorganisms, while the technical material cannot be reintegrated into the biosphere.

Typically, a large amount of biological material is produced by agro-industry activities. Therefore, recycling agro-industry by-products represents an important challenge for a circular economy. In this context, and as underlined by many studies [2–4], the waste by-product produced by the food and drink industries should be considered as one of the most serious environmental problems. In the drinks industries, for example, a brewery produces large quantities of by-products that include spent hops, yeast, and spent grain. The last of these is the most significant by-product in the brewing process, of which it represents 85% [5].

The latest Barth report on hops [6] reported that European beer production in 2018 was 531 million hectoliters, 401 million hectoliters of which was produced by the member countries of the European Union (EU 27). World production has instead been estimated at 1,904 million hectoliters. Considering that, for every 100 L of beer, 20 kg of brewers' spent grain (BSG) are produced [7–9], this estimates the worldwide annual production of BSG as ~38 to 39 million tons, with 3.4 million tons in the European Union alone [10].

Xiros and Christakopoulos (2012) [11] summarized the brewing process into the six key stages of malting, milling, mashing, brewing, cooling, and fermentation. As shown in Figure 1, after the mashing process, a filtration step (lautering) follows, from which a sweet liquid (the wort) is obtained. This liquid is rich in fermentable sugars that can be converted into ethanol during fermentation, while the insoluble, undegraded part of the malted barley grain is known as BSG [10,12].

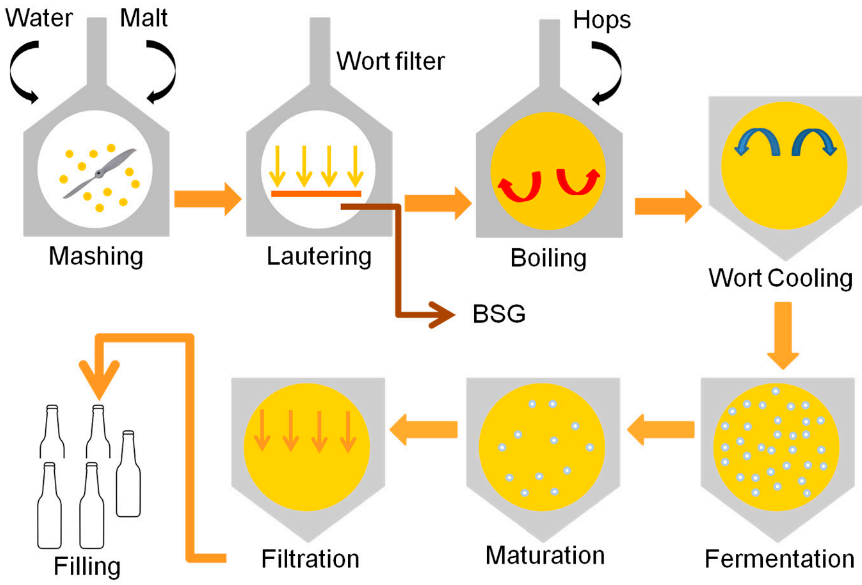

Figure 1. Simplified scheme for brewing. BSG, brewers' spent grain.

The disposal of BSG, spent hops, and yeast represents one of the major concerns for the brewing industry because of: (1) the huge bulk quantities generated; (2) the low market value; (3) the difficulty for their storage due to high moisture contents; and (4) the issues with their disposal as landfill or by burning due to environmental pollution [11].

In the last few years, following the fundamentals towards a circular economy, several ways to recycle BSG have been investigated. For example, Aliyu and Bala (2011) [13] reported that BSG has been investigated for animal feed, production of value-added compounds (e.g., xylitol, lactic acid, among others), microorganism cultivation, or simply as a raw material for extraction of compounds such as sugars, proteins, acids, and antioxidants. Mussatto and Roberto (2006) [14] highlighted that BSG can also be used efficiently for enzyme production, as an adsorbent for removing organic materials from effluents, and for immobilization of various substances.

However, to the best of our knowledge, little information is available on the possibility to recycle BSG through composting processes, to obtain an organic fertilizer. For this reason, and considering the main parameters requested for optimal development of the composting process, the objective of the present review was to use a literature analysis to determine whether the BSG microbial and physicochemical characteristics make it suitable for direct composting.

2. Different Utilization Routes of BSG, an Alternative to Composting—An Overview

Due to its high content in fiber, un-degradable protein, and water-soluble vitamins, BSG is typically recycled into livestock feed production [15–18]. This provides an alternative to the more expensive soybean as feed for ruminants and monogastric livestock, in its wet and dry forms, respectively [19]. However, the high protein content of BSG combined with its high moisture content and fermentable sugar content makes it particularly susceptible to microbial growth and subsequent spoilage over short periods of time, from 7 to 10 days [20,21]. To limit these undesirable effects and to encourage recycling of BSG into livestock feed, proximity between livestock farms and breweries would be appropriate. However, this is not always the case (e.g., breweries located in the cities) [22].

In its flour form, BSG is also used in human nutrition, as a source of fiber and protein [23–26]. Nevertheless, because of the changes to the flavor and physical properties (e.g., texture) of the final products, only relatively small quantities (i.e., 5–10%) can be incorporated [21,27]. Furthermore, as highlighted by Saba et al. (2019) [28], BSG can also be contaminated by mycotoxins, arising from cultivation of the barley to malt production, with the consequent problems for food security.

Brewers' spent grain is also widely used for renewable energy production, in the form of heat, biofuels, ethanol, and biogas [29–31]. In this context, Ortiz et al. (2019) [32] investigated the gasification technology for BSG use for syngas production. However, the chemical-physical characteristics of BSG, such as its low C/N ratio, can cause operational problems for anerobic digesters when BSG is used as the main substrate [33].

Brewers' spent grain can also be recycled to produce a substrate for microorganisms and enzymes [34], and for pigments, antifoaming agents, constituent materials (e.g., biodegradable film, building bricks), paper, absorbent substrates [35], and bio-covers for enhanced methane oxidation for landfill sites [36]. Chanzu et al. (2019) [37] reported that BSG can be used for the clothing industries, as a cost-effective sorbent material for wastewater decolorization.

These methodologies for BSG recycling often require a pre-treatment phase, which is typically a drying process. However, the drying phase represents an energy-intensive process [38], which could raise the costs for the breweries [39]. Jackowski et al. (2020) [40] have investigated the possibility of using hydrothermal carbonization process (HTC) as a pretreatment of BSG for subsequent use as a biorefinery feedstock. Meanwhile, Olszewski et al. (2019) [41] have evaluated the possibility of coupling HTC and pyrolysis, avoiding the drying process and related costs.

Many studies have also investigated the possibility of using BSG for agronomic purposes. In a study by Mbagwu and Ekwealor (1990) [42] BSG was used as a fertilizer when combined with mineral fertilizers, while in an agronomic trial, Aboukila et al. (2018) [43] combined BSG with composted material. Moreover, Saba et al. (2019) [28] carried out a study aiming at obtaining vermicompost using BSG mixed with cow manure, for use as a growth substrate for earthworms (*Eisenia fetida*). The same authors showed that vermicompost from BSG is enriched in bacterial taxa that can promote nitrogen immobilization in soil [44].

3. The Composting Process

Composting allows biological decomposition of organic matter and can be promoted by microorganisms under controlled conditions. In addition, as highlighted by Pampuro et al. (2016) [45], composting implies volume and weight reductions of the organic waste. This process is aerobic and exothermic, which leads to a stabilized final product (i.e., humus-like), known as compost, which is free of phytotoxicity and pathogens (i.e., viruses, bacteria, fungi, parasites), and is rich in nutrients. Hence, BSG has agricultural value as a fertilizer [46,47].

As shown in Figure 2, microorganisms are involved in this composting (i.e., bacteria, fungi, microarthropods), and they can easily metabolize and mineralize the simple organic carbon compounds, to produce ${SO_4}^{2-}$, NH_3, greenhouse gases, heat, and water vapor.

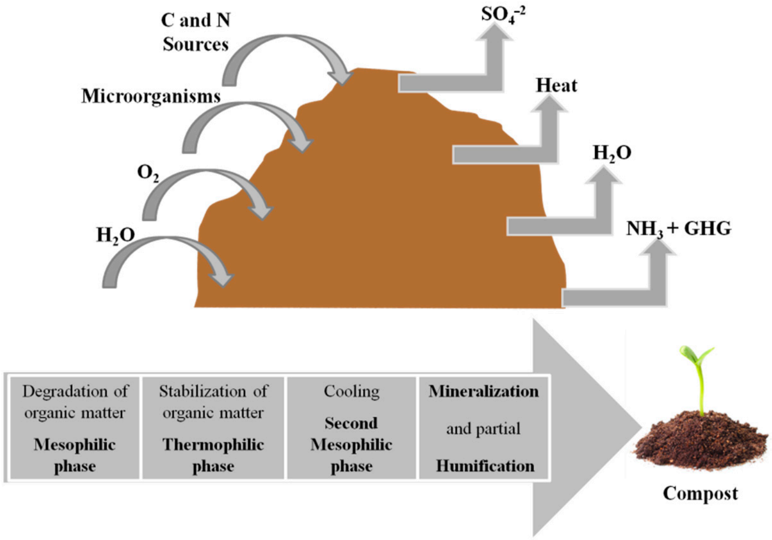

Figure 2. Scheme of the composting process. GHG, greenhouse gases.

In recent years, composting has gained interest as a waste management strategy that has potential economic and environmental benefits, as this process adapts to any by-product that results from agro-industry activities. Compost use for agricultural purpose can help to maintain and improve soil quality and fertility, while reducing erosion and allowing bioremediation of polluted soils [48,49].

3.1. Factors Affecting the Composting Process

Composting is a spontaneous process that occurs naturally. However, efficient composting to obtain a high value-added agricultural product in terms of agronomic properties, and to avoid nuisance problems such as odors and dust, requires the control of several factors. The composting process is typically affected by two main groups of factors: (i) those related to the composition of the initial composting mixture, such as its nutrient balance, pH, and porosity; and (ii) those related to the process management, such as O_2 concentrations and temperatures [50,51].

The nutritional balance of composting mixtures is strongly affected by the C/N ratio. Microorganisms involved in the composting process require both carbon and nitrogen as organic sources for their activities and development. Following the recommendations of De Bertoldi et al. (1983) [52] to optimize the development of the composting process, the C/N ratio should be from 20 to 30. Composting mixtures characterized by an excess of degradable substrate for the microorganisms typically have a C/N ratio >30, which makes the process very slow. On the other hand, as highlighted by Bernal et al. (2009) [51], composting mixtures characterized by a C/N ratio <20 can result in nitrogen losses, as ammonia volatilization or as leachate from the composting mass. However, low C/N ratios can be corrected by adding a bulking agent (e.g., straw, wood chips, sawdust) to provide degradable organic carbon.

According to Bernal et al. (2009) [51], the optimum pH when composting is from 5.5 to 7.5. This factor has a key role in the control of nitrogen losses through ammonia volatilization. In this context, Azim et al. (2018) [53] highlighted that ammonia losses can be particularly significant at pH > 8.

In terms of porosity, air-filled pore spaces of composting piles should be in the range of 35% to 50%. Porosity >50% prevents the temperature increase inside a composting pile, because energy loss exceeds heat production. Porosity <50% can instead lead to anaerobic conditions and odor generation [51].

For aeration, the optimum O_2 concentration is from 15% to 20% [54]. This parameter presents a significant influence on composting development. Correct aeration controls the temperature, removes the excess moisture, and provides the O_2 required by the biological processes.

The optimum moisture content of compost is from 60% to 65%. Moisture >65% represents an obstacle to the supply of oxygen, and anerobic conditions can be generated. On the other hand, microbial activity is significantly reduced with moisture <40% [55].

The temperature pattern for compost follows the microbial activity and the composting process. The optimum temperature range for composting is 40 °C to 65 °C. Temperatures >55 °C can kill pathogenic microorganisms such as *Aspergillus fumigatus*, the populations of which drop significantly at >50 °C. Other pathogenic microorganisms, such as *Salmonella* spp. and the nonpathogenic *Escherichia coli*, have been reported to persist during composting of several types of waste [56]. Thus, it has been suggested that 70 °C for 30 min or 65 °C for several hours are required to obtain a well-hygienized end-product [52]. However, if the temperature achieved exceeds the tolerance range of the thermophilic decomposers, the effect is damaging for composting [51]. For this reason, temperature control is required to optimize the composting process. Several strategies have been identified for excess heat removal: control of the size and shape of the composting mass [57]; improved cooling and favorable temperature redistribution by turning operations, which means heat removal through evaporation cooling [58]; and superior temperature control by active removal of heat through temperature feedback-controlled ventilation (Rutgers strategy).

Considering the development of the temperature profile, composting can be divided into three main phases:

- Mesophilic phase (25–40 °C): initially fungi, actinomycetes, and bacteria metabolize energy-rich and easily degradable compounds, such as sugars and proteins, to result in increased temperatures.
- Thermophilic phase (35–65 °C): with increasing temperature the decomposition continues to be rapid up to 62 °C, when the mesophilic flora are completely replaced by the thermophilic flora. These latter include, in particular, heat-tolerant and thermophilic bacteria (e.g., *Bacillus* spp., *Thermus* spp.) and actinomycetes (e.g., *Thermomonospora* spp., *Thermoactinomyces vulgaris*, *Streptomyces* spp., *Microtetraspora* spp.). Thermophilic fungi have optimal growth temperatures between 35 °C and 55 °C, and at higher temperatures their growth is inhibited. The thermophilic phase is important for elimination of pathogenic microorganisms, which is also due to some actinomycetes, such as *Streptomyces* spp., as known producers of antibiotics (e.g., erythromycin, neomycin, chloramphenicol, streptomycin, tetracycline).
- Cooling phase (or second mesophilic phase): when the activity of the thermophilic microorganisms ceases due to substrate exhaustion, the temperature begins to decrease. Mesophilic bacteria can then re-colonize the substrate, particularly the sporogenic *Bacillus* spp. and *Clostridium* spp. [59]. The second mesophilic phase is characterized by increasing numbers of bacteria and fungi that degrade polymers such as starch and cellulose.

The second, stabilization, phase includes not only the mineralization of more slowly degradable compounds, but also more complex processes, such as humification of lignocellulose compounds [60]. In this phase, the quality and maturity of the compost is determined through various chemical parameters, such as pH, ammonia content, and C/N ratio, as well as microbiological and biological aspects, such as plant growth and seed germination.

3.2. Methods for Identification of Microbial Communities in Composting

The study of microbial communities in the raw materials and throughout the composting process is fundamental to monitor and manage the quality of soil improvers that are obtained from the stabilization processes. The methods to determine the diversity of the microbial communities are of two types: (i) those based on the cultivation of microorganisms in specific media, for evaluation of the richness and abundance of the cultivable microbial species; and (ii) culture-independent methods for the study of the microbial communities as a whole, without the need to isolate and identify single species. The latter methods are based on various molecular biology techniques, among which denaturing gradient gel electrophoresis has been widely used for characterization of the structure of bacterial communities, in both soil and water samples [61].

3.3. Dynamics of Microbial Species during Composting

Each raw material contains its own particular microbiota and provides a unique environment for that community [62]. The biological and physicochemical parameters of each material influence the composition and dynamics of the species progression during the composting process. Indeed, pH and total nitrogen of the composting material positively influence the microbial communities, and conversely, total organic carbon content and seed germination indices are negatively correlated [63]. The bacterial community structure within different composting materials are all significantly influenced by the C/N ratio and moisture, with an optimal range for the C/N ratio of 20 to 30. Thus, microbial communities can be effectively regulated by adjusting the relevant environmental parameters [64]. Through cultivable approaches, air-dried BSG has been shown to be contaminated by bacteria (103 CFU/mg), but not by fungi and yeast [28]. However, the presence of thermal resistant mycotoxins, such as ochratoxin A, fumonisins, T-2, and HT-2, suggests that microbiological analysis should be performed for raw and stored BSG to determine the microbial species structure, to assess BSG safety and suitability for composting.

Wang et al. [64] compared the bacterial structure of seven different composts using denaturing gradient gel electrophoresis (DGGE), and they showed that four species were present in all of the compost types, two species in several composts, and four species were specific of a single compost. He et al. (2013) [63] showed that *Arcobacter* spp. and *Marinospirillum* spp. were dominant prior to composting, whereas *Thermotogae* spp. became more strongly represented as the composting process proceeded. *Bacillus* spp. and *Cohnella* spp. were identified at various composting phases, while *Cellulomonas* spp. and *Cytophaga* spp. were present during the aerobic mesophilic phase of cellulose degradation. More than half of the *Bacillus* spp. examined produced extracellular cellulases, which included in particular, mesophilic aerobic and anaerobic forms of *B. subtilis*, *B. polymyxa*, *B. licheniformis*, *B. pumilus*, *B. brevis*, *B. firmus*, *B. circulans*, *B. megaterium* and *B. cereus*; these are known to be cellulose and hemicellulose degraders [65].

Actinomycetes show primary biodegradative activity, as they can secrete a wide range of extracellular enzymes and can metabolize recalcitrant compounds. Thus, composting relies heavily on such prolific actinomycetes activities. As well as the mesophilic *Cellulomonas* spp., thermophilic cellulose degrading *Thermoactinomyces* spp., *Streptomyces* spp., and *Thermomonospora* spp. have been isolated from dry vermicompost at high salt and alkaline pH [34]. Finally, fungal species are also known to have important roles in composting of lignocellulosic materials, such as *Trichoderma harzianum*, *Pleurotus ostreatus*, *Polyporus ostriformis*, and *Phanerochaete chrysosporium*.

4. Characteristic of Brewers' Spent Grain Related to the Composting Process

Many factors contribute to the high variability of BSG, including region of production [66], barley variety, harvest time, hop characteristics [67], malting and mashing conditions, and quality and type of adjuncts added during the brewing process [68]. Table 1 reports the main physicochemical characteristics described for BSG with respect to the major factors that affect the composting process.

The C/N ratio, pH and moisture content of BSG described in the literature range from 7.1 to 26.5, from 3.8 to 6.9, and from 70.6% to 81.3%, respectively (Figure 3). Considering the main parameters that affect the composting process, as shown in Figure 3, the C/N ratio identified for BSG in the literature can be much lower than the best composting target range (20–30). The optimum pH for aerobic stabilization of compost ranges from 5.5 to 7.5, while the pH reported in the literature for BSG is typically more acidic. Also, the mean moisture content described in the literature for BSG is higher than the moisture recommended for composting, with a range of 60% to 65%.

Table 1. Physicochemical characterization of brewers' spent grain, expressed on a dry weight basis.

Source	Total Nitrogen (%)	Total Carbon (%)	C/N Ratio	pH	Moisture (%)
Aboukila et al., 2018 [43]	6.1	43.5	7.1	4.2	75.0
Babatunde et al., 2015 [69]	-	46.4	-	-	-
Bougrier et al., 2018 [70]	4.4 *	-	-	-	75.3
Buffington 2014 [71]	-	49.1	-	-	-
Ferreira et al., 2019 [72]	5.5	48.3	8.8	-	78.8
Khidzir et al., 2010 [66]	3.8 *	35.6	9.5 *		72.6
Mainardis et al., 2019 [73]	2.7	46.6	17.6	5.8	77.0
Manolikaki and Diamadopoulos 2020 [74]	4.8	45.0	9.4 *	4.8	-
Mbagwu and Ekwealor 1990 [42]	5.1	-	-	4.4	-
Oliveira et al., 2018 [75]	4.6 *	-	-	6.9	78.1
Ortiz et al., 2019 [32]	3.5	48.7	13.9 *	-	76.0
Panjičko et al., 2017 [31]	5.1	58.0 *	11.4 *	-	76.3
Pérez et al., 2017 [76]	4.4	50.4	11.5 *	-	81.3
Phyllis2 Database [77]	3.7	48.9	13.2 *	-	78.9
Saba et al., 2019 [28]	3.6	37.6 *	10.3	3.8	-
Siva Shangari and Agamuthu 2012 [36]	3.6 *	40.1	11.0	4.4	70.6
Sperandio et al., 2017 [78]	4.2	45.7	10.9 *	-	72.9
Stocks et al., 2002 [79]	2.0	50.9	25.5	-	76.0
Thomas and Rahman 2006 [80]	2.0	53.0	26.5 *	-	73.7
Vitanza et al., 2016 [81]	4.1 *	50.8 *	12.4	-	81.3

*, inferred or calculated; -, value absent and impossible to infer.

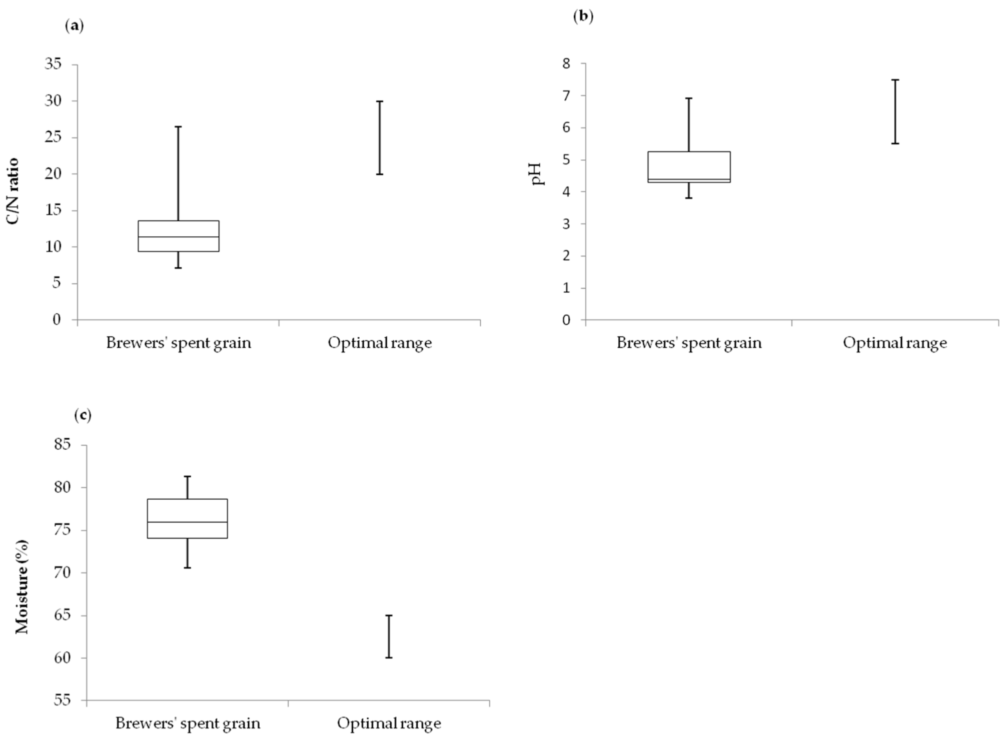

Figure 3. Brewers' spent grain compositions and optimal composting ranges for C/N ratio (**a**), pH (**b**), and moisture content (**c**). Whiskers indicate minimum and maximum levels, and horizontal bar in the box indicates the median.

5. Ways to Optimize the Composting of BSG

To optimize C/N ratio, air spaces, and pH when composting, the initial mixtures should be prepared by mixing BSG with a lignocellulosic bulking agent. Addition of livestock manure should also be provided for the starting material, to promote the composting process. Indeed, to optimize the initial C/N ratio (20–30), the BSG quantity can be calculated according to Equation (1) [82]:

$$M_{BSG} = \frac{[R \times M_{man} \times N_{man} \times (100 - U_{man})] + [R \times M_{str} \times N_{str} \times (100 - U_{str})] - [M_{man} \times C_{man} \times (100 - U_{man})] - [M_{str} \times C_{str} \times (100 - U_{str})]}{[C_{BSG} \times (100 - U_{BSG})] - [R \times N_{BSG} \times (100 - U_{BSG})]} \quad (1)$$

where R is the C/N ratio target (set at 30) and M, N, U, and C are the weight (in kg), total nitrogen content (in %), moisture content (in %) and total carbon content (in %), of the BSG, livestock manure (man; solid pig slurry, sheep manure), and wheat straw (str). All of these quantities on the right of Equation (1) should be previously fixed.

Below, we consider two hypothetical composting mixtures:

1. BSG + wheat straw + pig slurry solid fraction.
2. BSG + wheat straw + sheep manure.

Tables 2 and 3, respectively, report the characteristics for the compositions of these two hypothetical organic materials for the composting process. For the wheat straw, pig slurry solid fraction, and sheep manure, the investigated parameters were previously analyzed in the laboratory. Instead, for the BSG, the reported values are the means of the values from Table 1. Equation (1) was then used to calculate the amount of BSG required to optimize the initial composting mixture.

Table 2. Compositions of a hypothetical pig slurry composting mixture.

Composting Mixture	Parameter					
	Weight (kg)	Moisture (%)	Total Carbon (%)	Total Nitrogen (%)	C/N Ratio	Weight Percent (%)
Brewers' spent grain	20.2	76.3	47.0	4.1	13.3	40.2
Wheat straw	10	8.0	55.4	0.3	205.2	19.9
Pig slurry solid fraction	20	66.3	46.3	1.9	24.4	39.9
Total	50.2	-	-	-	-	100.0

Table 3. Compositions of a hypothetical sheep manure composting mixture.

Composting Mixture	Parameter					
	Weight (kg)	Moisture (%)	Total Carbon (%)	Total Nitrogen (%)	C/N Ratio	Weight Percent (%)
Brewers' spent grain	16.5	76.3	47.0	4.1	13.3	31.5
Wheat straw	16	8.0	55.4	0.3	205.2	30.4
Sheep manure	20	62.7	45.8	3.3	13.9	38.1
Total	52.5	-	-	-	-	100.0

In this way, the BSG formulated here can be re-used as a new resource material, such as a soil fertilizer and conditioner, to replace the more expensive and less environmentally sustainable chemical fertilizers for crop production [83,84]. However, immature compost can generate adverse effects on plant growth and/or seed germination [85]. Therefore, phytotoxicity might represent an important indicator of compost quality. Phytotoxic effects of organic wastes are the result of the combination of several factors, including ammonia, salts, heavy metals, and low molecular weight fatty acids [46,86]. Several chemical and biologic parameters have been used to determine compost maturity, such as temperature, pH, C/N ratio, humification ratio, electrical conductivity, ammonia nitrogen (NH_4-N), ammonia–nitrate nitrogen ratio (NH_4-N/NO_3-N) and germination index [87,88]. For these reasons, to make a qualitative evaluation of the process and the final product, these parameters should be monitored.

6. Conclusions

In accordance with the definition of a circular economy, the composting process is a means for the conservation of resources and a way to help to close the circle. However, as previously reported, due to its chemical characterization, BSG is not suitable for direct composting. The addition of lignocellulosic bulking agents to the BSG, such as wheat straw, woodchips, or sawdust, improves the reduction of the moisture content during the composting process. The addition of these carbon-rich by-products can also enhance the optimization of the substrate properties, such as its C/N ratio, air spaces, and pH, to affect the composting process thus positively. Moreover, the addition of livestock manure is needed for the starting material to promote the composting process.

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