UNDERSTANDING BIOWASTE COMPOSTING IN DEVELOPING COUNTRIES: LESSONS FROM COLOMBIA

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Abstract

In developing countries, composting implementation has faced limitations that puts the sustainability of these systems at risk. This paper integrates results from research published by the authors aiming to increase the understanding of composting performance in developing countries and to identify strategies that contribute to its improvement. First, a summary of a systemic analysis developed by the authors using systems thinking tools, like causal diagrams, is presented. This analysis allowed us to identify four subsystems: product quality and commercialization, technology, substrate characteristics, and business and financial management. Second, the variability of the substrates in a biowaste (BW) composting plant is analyzed. To achieve this, 39 representative samples, taken at the time of piles formation, were evaluated. High variability was found in five from the eight physicochemical parameters analyzed (i.e. N_{Total}, C / N, K_{Total}, P_{Total}, Ash), as well as limitations in substrate quality for composting. Third, locally available bulking materials to improve substrate quality were selected, considering context limitations in the study site such as the BW and, socioeconomic and technical criteria. Finally, a pilot-scale experiment was developed to evaluate the effect on the composting process and product quality of incorporating two of the selected bulking materials. In this experiment, a decrease in process times, and an improvement in the degradation rates of substrates and in the product quality were found. The aforementioned research has allowed a better understanding of the composting process performance in developing countries and identified strategies that can contribute to its improvement

Keywords: composting, developing countries, sustainability, small city, systemic analysis, biowaste

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1. Introduction

In developing countries, composting has been used as one of the alternatives for biowaste (BW) management [1-2] and is considered as a method of simple operation and low-cost compared to other alternatives [3-5]. In addition, composting generates a product that can be used as soil improver or for crop fertilization [6]. However, different experiences show that composting implementation in developing countries has not met the expectations and generates products that fail to achieve quality standards recommended for different uses. This prevents commercialization and marketing and affects the financial sustainability of the composting facilities [2-3, 7-8].

Research has been conducted in developing countries aiming at BW composting optimization. However, these studies address specific dimensions of BW composting implementation, specifically the technical and technological components, such as incorporation of different amendments or bulking materials [9-12], or aspects regarding the improvement of product quality [3, 13-18]. Zurbrügg et al. [19] indicate that the operation of BW composting systems not only depend on technological aspects, but is also related to other aspects of municipal solid waste (MSW) management, such as social, institutional, political, regulatory, economic, and financial ones. From the analysis of the composting system performance, including technical and non-technical elements, strategies for improvement can be identified.

This paper integrates results of independently published research from the authors on the topic of BW composting in the context of developing countries. Initially, an analysis of the BW composting performance in developing countries, prepared using systems thinking tools (causal diagrams) is presented [20]. This analysis facilitated the identification of strategies in the technical and non-technical dimensions for the improvement of the composting process. In addition, from this analysis, it was rendered necessary to study in greater depth aspects such as: i) characteristics and variability of substrates (BW) [21]; ii) selection of amendment or bulking materials to improve the quality of the identified substrate [22]; iii) effect of adding selected amendment or bulking materials on the process and product quality [23]. Finally, based on the results obtained, a brief reflection on the research trends of BW composting in developed countries is presented.

2. Materials and methods

2.1. System analysis of biowaste composting

Causal diagrams, a tool from the systems thinking paradigm, were used to develop this analysis. Causal diagrams were built using information obtained from: i) follow up to operation and monitoring of five composting facilities in Colombia; and ii) literature review about experiences of BW composting implementation in developing countries. Follow up to the operation and monitoring of the composting facilities was developed through: interviews; inspections; characterization and sampling of substrates and products; and review of secondary data related to operation, management and product marketing. Table 1 shows general features of the studied facilities.

Table 1. Characteristics of the five BW composting facilities in Valle del Cauca, Colombia

Location	Urban Population	Waste Processed (t month^{-1})	Composting Method	Type of Substrate
Alcalá	9106	60.0	WMT	SSBW
Bolívar	3621	17.3	SPPA	MBW
El Dovio	5175	39.1	SPPA	SSBW
La Victoria	9265	84.1	SPPA	MBW
Versalles	3831	18.9	WMT	SSBW

WMT: Manually turned windrows (i.e. windrows turned by an operator with shovels); SPPA: Static piles with passive aeration via natural ventilation without turning; SSBW: biowaste derived from source separated MSW; MBW: biowaste derived from commingled MSW.

The literature review focused on the search of scientific literature reporting experiences regarding BW composting implementation. This search was conducted on databases such as: Scopus®, Sciencedirect®, EBsco®, and Scielo®.

The review was developed using keywords such as: "biowaste composting", "developing countries", "sustainability", "performance", among others. Although, the focus was developing countries, experiences from developed countries addressing composting from a holistic perspective were also considered. Greater detail on data collection and a literature review have been published in Oviedo-Ocaña et al. [20].

After collection of data from the composting facilities, a workshop with representatives from the composting facilities was carried out. This workshop allowed to identify the elements that integrate the BW composting system in the studied context, and were grouped in four subsystems, according to main dimensions identified from the literature review. The identified elements were reviewed, defined and adjusted by an expert panel, consisting of five researchers in solid waste management and BW composting. In addition, this panel analyzed relations between the elements and prepared a preliminary version of the causal diagrams integrating the identified elements. The causal diagram was reviewed and drawn using the Vensim software in its free version. This diagram was analyzed and allowed the proposal of strategies to improve the performance of the composting systems. These strategies were integrated to the causal diagram as well.

2.2. Evaluation of the substrate quality entering BW composting facilities

One of the five municipalities with composting facilities analyzed was selected (See Table 1). Criteria considered for selection were: i) the composting facility should be in operation; ii) source separation and selective collection should be carried out; iii) managing organization should be willing to take part in the research. The selected municipality, Versalles, has a temperature of 18°C, and an average rainfall of 1500 mm/year. 80% of the population practiced source separation and 94% used plastic bags for the storage of BW. The collection service included selective collection two times per week (Mondays and Thursdays). Therefore, the BW was stored either three (i.e. Mondays to Thursdays) or four (i.e. Thursdays to Mondays) days within the households. SSBW was transported in dump trucks to the composting facility in which residual non-biodegradable materials were manually separated. In the facility, piles forming was developed 24 hours after the entry of wastes, with a weight between 2.8 and 3.9 t, twice a week (i.e. Tuesday and Friday).

During pile formation, BW were manually homogenized. Composting piles had conical shape, approximate height of 1.1 m, and were placed on an impermeable and covered surface. Composting piles were manually turned and moisturized. The physical composition and physicochemical characterization of the inlet (SSBW) were based on samples made of sub-samples obtained after the formation of the composting piles. The sampling procedure was described by Oviedo-Ocaña et al. [21]. To reduce the experimental error, sampling activities were performed throughout the study by the same operator, who had been previously well trained. This characterization process was developed during 15 months during which 39 samples were obtained.

The physical composition was determined and classified into nine categories (see Table 2), namely: i) Citric/semi-citric fruits; ii) Non-citric fruits; iii) Vegetables, legumes, and leguminous plants; iv) Plantains and tubers; v) Unprocessed food Mixtures; vi) Processed food; vii) Pruning and garden waste; viii) Paper and cardboard; y ix) Other non-biodegradable material. Categories i – v corresponded to unprocessed food types, whilst Category (vi) was the processed food. These categories were proposed after taking into account the studies of Parfitt et al. [24] and Gustavsson et al. [25]. The physicochemical characterization of the SSBW samples involved the following variables and methods: potassium (K_2O), total oxidizable organic carbon (TOC), total phosphorus (P_2O_5), ash content, pH, and moisture content - according to Standard NTC 5167 [26]; total nitrogen (N_{TOTAL}) according to Standard NTC 370 [27].

The individual behavior of the physical composition and physicochemical characteristics of each substrate was analyzed by using central tendency measures and other descriptive statistics (mean, variance). High heterogeneity was considered when CVs (coefficients of variation) exceeded 20%. The statistical processing was performed using the data analysis software R®, version 2.15.2 and Minitab® v.17.

2.3. Selection of amendments and bulking materials for BW composting

Based on analysis of the substrate, a literature review and the characteristics of the municipality, strategies were proposed to improve the substrates quality and the processing conditions. This included the addition of locally available amendments and bulking materials. To this end, an inventory of amendment or bulking materials locally available was conducted by visiting farms in the agricultural sector and checking business records in the municipality (i.e. six materials were identified). Subsequently, the selection of the materials was carried out through a tool that included qualitative and quantitative variables. Table 2 shows the tool for the selection of materials. The detailed description of the criteria used in the selection tool and the measurement tool is shown in Oviedo-Ocaña [22].

Table 2. Tool for the selection of amendments or bulking materials

%[1]	Indicators	%[2]	Measurement	Potential values	Desired values	Score (points)
25	Required quality[3]	28	C/N criterion	Yes/No	Yes	Yes: 5
		24	Moisture criterion	Yes/No		
		24	pH criterion	Yes/No		
		12	Other nutrients criterion	Yes/No		No: 1
		12	Porosity increase	Yes/No		
20	Required quantity	100	Required Quantity of material (RQM) to complement substrate in terms of weight	-99% <RQM<99	Quantity between 0 and 15%	<0%: 0 > 30%: 1 >15% and < 30%: 3 >0% and < 15%: 5
15	Lower acquisition cost (Ind_{cost})	100	Cost of material / higher cost of all materials	$Ind_{cost} \geq 0$	$Ind_{cost} \leq 0,5$	$Ind_{cost} < 0,5$: 5 $Ind_{cost} \geq 0,5$: 1
10	Access to obtain the material	100	Type of access road	Very good Good Acceptable Bad Non-existent	Paved	Very good: 5 Good: 4 Acceptable: 3 Bad: 2 Non-existent: 0
10	Distance to the agrosystem (AS)	100	Distance to AS (D)	$D \geq 0$	D = 0	D = 0 km:5 1 < D< 3 km : 4 $3 \leq D < 5$: 3 $D \geq 5$:1
10	Availability for delivery of the material	100	It has restrictions for continuous supply	Yes No	No	Yes: 1 No: 5
10	Simplicity for material handling	100	Operational requirements	Sorting and shredding Shredding Does not require	Does not require	Clasif. and shredding.: 1 Shredding: 3 Does not require: 5

Note: [1,2]percentages which were selected arbitrarily

2.4. Effect of adding selected amendment or bulking materials (BM) on the composting process and product quality

Experiments were carried out with the two materials (BM) that had better results in the assessment using the selection matrix (see section 2.3): sugarcane bagasse (SCB) and star grass (SG). The first experiment tested two treatments: A (78% BW + 22% SCB) and B (100% BW). In the second experiment, the treatments were: C (66% BW + 34% SG) and D (100% BW). Each treatment had triplicates (i.e. tree piles per treatment). Details regarding the definition of the treatment proportions (A and C) are described in Oviedo-Ocaña et al. [23]. Substrates had the characteristics shown in Table 3.

Table 3. Physicochemical characterization of the substrates in experiments 1 and 2.

Parameters	Units	Substrate A	Substrate B	Substrate C	Sustrate D
pH	Units	5.57	5.67	6.12	5.39
Moisture	% wb	65.7 ± 1.90	70.8 ± 5.88	72.46 ± 1.63	78.99 ± 0.82
TOC	% db	37.32 ± 2.00	27.26 ± 1.50	25.85 ± 0.93	25.94 ± 0.02
N_{Total}	% db	1.17 ± 0.02	1.27 ± 0.00	1.48 ± 0.02	1.08 ± 0.02
C/N	-	32.0	21.5	17.47	24.02
Ash	% db	21.87 ± 0.09	34.38 ± 1.03	35.54 ± 0.14	31.00 ± 0.90
K_{Total}	% db	1.33 ± 0.02	1.06 ± 0.01	2.05 ± 0.10	1.75 ± 0.03
P_{Total}	% db	1.06 ± 0.09	0.64 ± 0.05	0.59 ± 0.01	0.21 ± 0.01

[a]Average ± standard deviation.
TOC: total organic C; N_{Total}: total N; C/N: carbon nitrogen ratio; K_{Total}: total K, P_{Total}: total P.

Piles weighed 318 kg in experiment 1 and 258 kg in experiment 2 and were operated under identical environmental conditions (impermeable surface and covered roof). A 2-m distance was kept between the piles. Table 4 includes all monitoring parameters.

Table 4. Monitoring parameters and methods

Parameter	Frequency of measurement	Method	Equipment
pH	At least twice a week	--	30-cm thermometer
Temperature	Daily	Potentiometric	pHmeter (WTW Model 315i)
Moisture	At least three times a week	Gravimetric	Moisture meter Ohaus MB-35
Germination index (GI)	At least three measurements at the end of the monitoring	Sensibility of the radish (*Raphanus sativus* L.)	According to Varnero et al. [28]

Moisture was kept to 40% by adding water. A turning process was used when the piles reached temperatures of 65 °C or higher and to avoid compaction of the materials. A continuous monitoring of the process was performed until piles reached close to ambient temperatures (± 5 °C) and until the products acquired smell of soil. Both criteria indicated the end of the maturation phase. Additionally, during the maturation phase, self-heating tests were performed to verify if any increase of the temperature would occur during the process.

At the end of the process, representative samples were taken to assess product quality. Parameters tested were: K_{Total}, TOC, P_{Total}, ash content, pH, cation-exchange capacity (CEC), electrical conductivity, water holding capacity (WHC), and moisture content according to Standard NTC 5167 [26]; N_{Total} according to Standard NTC 370 [27]. Microbiologic assays (total coliforms and total fecal coliforms were performed according to the norm of the United States Environmental Protection Agency [29]). Quality parameters were compared to standard values established by the corresponding Colombian Norm [26].

2.5. Future perspectives for biowaste composting research in developing countries

From the systemic analysis and the aforementioned experiments, tendencies for future research on biowaste composting in developing countries were formulated and discussed.

3. Results and Discussion

3.1. Systemic analysis of biowaste composting

As part of our research, a systemic analysis of the implementation of composting in small cities in developing countries was prepared. Four subsystems were identified: i) product quality and commercialization, ii) business and financial management, iii) substrate characteristics and, iv) the technological component. Those four subsystems comprised interacting elements (See Figure 1). Table 5 shows a description of subsystems of biowaste composting system in developing countries.

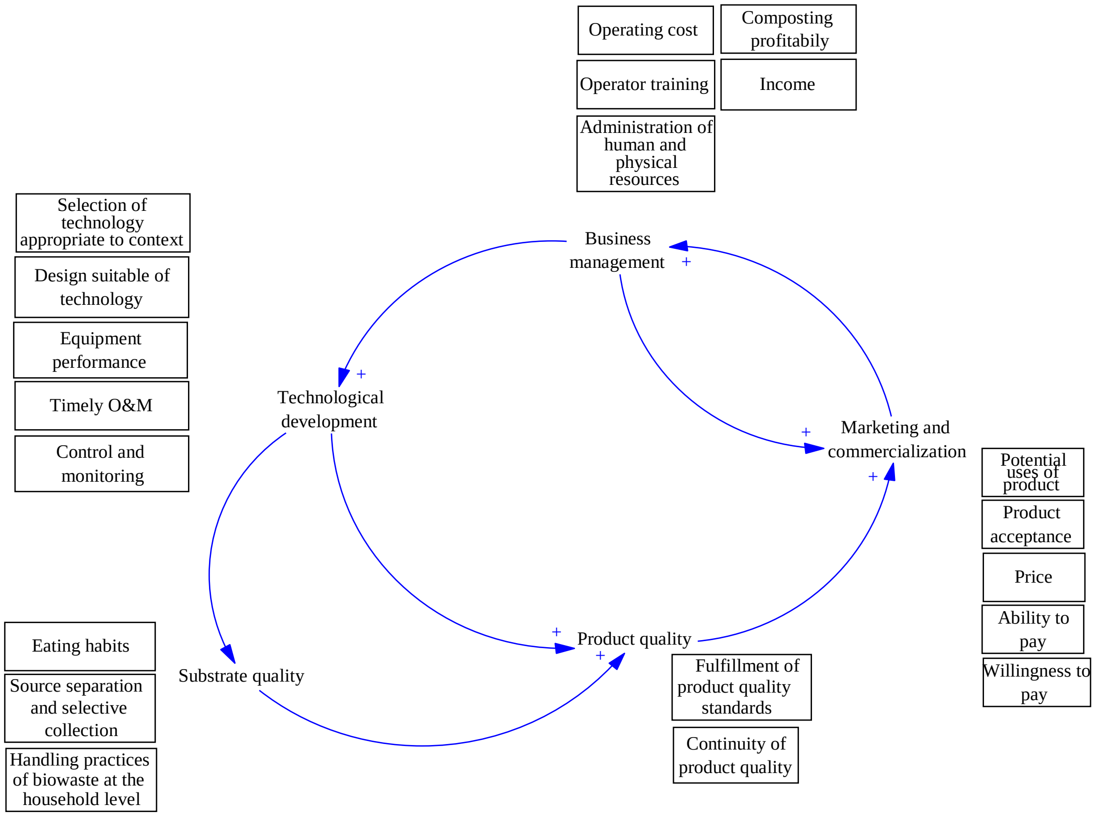

Figure 1. Causal diagram for the general biowaste composting system

Table 5. Description of the four subsystems of biowaste composting systems

Subsystems	Description
Product quality and commercialization	This subsystem refers to the quality of the product according to its agronomic properties and pollutants' content (i.e. content of heavy metals, salts, priority pollutants). These elements determine potential uses (i.e. amendment material, fertilizer, or cover material) and may limit the use of the product due to health or environmental risks [30]. The lower variability in the physicochemical quality of the product and the constant availability in terms of quantity and price can generate greater product acceptance among users and continuous sales with an impact on the commercial sustainability of the product [31]. Greater acceptance of the product could generate a higher willingness to pay (according to the user's ability to pay). Additionally, understanding the long-term effects of compost on soil may promote a better product marketing in the future.
Business and financial management	Income from product commercialization contributes to the economic sustainability of facilities and with resources for O&M, monitoring, marketing, and administration. Composting should be considered not only as an option for waste treatment but also as a productive process that generates income from product sales [8]. However, product commercialization hardly covers operational costs. Managing composting with a business perspective (administrative, commercial, technical, and economic aspects) contributes towards improved resources administration (human, material, and equipment), organizational planning, and connections with external agents who can provide financial, commercial, technical, and research support. It also enables strengthening commercialization management which aids to identify market segments with potential product users and to increase the levels of user satisfaction. Informality in process administration creates operational deficiencies, which affect product quality [8].
Substrate characteristics	Product quality is dependent on substrate characteristics (mixture level e impurities and other physicochemical characteristics, such as organic matter, nutrients, moisture, and pH). Source separation and selective collection have proved to effectively decrease levels of biowaste impurity [32-33], reducing the number of rejections, operational activities and ensuring larger amounts of

	biowaste with adequate conditions for processing. The physicochemical quality (nutrients, pH, and moisture) can be controlled at facilities (at least twice annually), thus, it is considered in the technological component subsystem.

Continuation Table 5. Description of the four subsystems of biowaste composting systems

Subsystems	**Description**
Technological component	Substrate physicochemical characteristics are influenced by physical composition, which is related to food consumption habits, waste handling practices and conditions of the cleaning service provision [34]. These elements are variable and influence the physical and chemical characteristics of the substrates. It makes important their consideration in the design of the facilities and in the operation and monitoring of the process (substrate quality control) to ensure that prior conditioning is given to substrates before processing. Technology selection is essential together with consideration of the main parameters that control the process: i) environmental (temperature, moisture, pH and aeration), and ii) substrate physicochemical characteristics. Technology selection and design, and control and monitoring schemes for operation require detailed knowledge of the local social, economic, and cultural conditions, as well as substrate characteristics. In developing countries, in the stage of technology selection, the low level of human resources training and the typically limited economic resources for investment and O&M should be considered [35]. Technological development adapted to local conditions improves operation and performance of facilities, which can favor the amount of materials recovered, and positively influence systems sustainability [19].

Source: Adapted from Oviedo-Ocaña et al. [20].

The systemic analysis helped to elucidate key strategies to improve biowaste composting sustainability: promoting administration within a business perspective, promoting marketing and commercialization initiatives, and implementing local technological development. In addition, some strategies more distant along the causal chain were proposed such as: developing standards and public policies to promote source separation, recognizing the economic and environmental benefits of composting, encouraging the use of products, such as compost, setting product quality standards in accordance with the potential uses of products and supporting technological development.

3.2. Evaluation of the substrate quality in BW composting facilities

BW were characterized by the predominance of non-processed food (92.9±4.0%), followed by processed food (2.0±1.8%), paper and cardboard (2.0±1.5%), pruning and garden waste (1.7±1.3%), and other non-biodegradable materials (1.4±1.0%). Among the non-processed food, the constituents that predominated were: unprocessed food mixture (35.7%), plantains and tubers (32.6%), citric fruits (12.9%), non-citric fruits (4.7%), vegetables, legumes and leafy greens (7.1%). It is observed that the substrates of the composting facilities are mainly composed of non-processed food. The proportion of processed food was low because of the habit of using this type of waste for activities such as animal feeding [34]. Likewise, the minimum proportion of other non-biodegradable material is emphasized, which is associated to the effectiveness of the source separation activities and selective collection.

Significant variability was found in five quality parameters that were analyzed in the inlet stream, with corresponding coefficients of variation (CV) higher than 23% (See Table 6). The substrate exhibited the typical characteristics found in food waste, such as acidic pH, a high moisture content, and a low C/N ratio during the process. The potassium contribution from plantain skins and the phosphorus deficiency may limit the nutritional value of the product.

On the other hand, the effect of the variability of the inlet material on the variability of the end-product was determined [21]. These results reveal that a rather high variability in the physicochemical quality of the substrates, influences the variability found in the products too. Although, one would expect that the variability of the compost parameters would decrease, due to mixing, it remained mostly similar to that of the inlet material. This high variability of the product quality parameters can be associated not only to the variable conditions of the inlet substrates (e.g. variability of inorganic impurities) but also to the varying operational conditions on the composting piles and to the variable nutrient and microbial process dynamics. This feature highlights the need to control those parameters when designing and operating composting facilities. In addition, results imply that the maintenance of a uniform quality of the feed material into a composting facility is crucial to maintain a product of consistent quality.

Table 6. Physicochemical characteristics of the raw substrates and of the product

Variable	Unit	Substrates based on n = 39 (biowaste) Pooled mean ± Std	Coefficient of Variation (%)
pH	--	5.5 ± 0.5^{N}	9.09
Moisture	%	76.7 ± 3.2^{N}	4.17
TOC	% (db)	32.8 ± 4.8^{N}	14.55
N_{TOTAL}	% (db)	1.6 ± 0.5^{NN}	31.25
C/N	--	21.7 ± 5.3^{N}	24.42
K_{TOTAL}	% (db)	1.6 ± 0.5^{N}	31.25
P_{TOTAL}	% (db)	0.3 ± 0.1^{NN}	33.33
Ash	% (db)	25.1 ± 5.6^{N}	22.52

Source: Adapted from Oviedo-Ocaña et al. [21]. d.b.: dry weight basis; N: normally distributed data according to the Shapiro-Wilk test at α=0.05; NN: non-normally distributed data according to Shapiro-Wilk test at α=0.05.

3.3. Selection of amendment and bulking materials

Based on the analysis performed, the substrate for the BW composting process lacked favorable conditions due to predominant features such as: pH in the acidic range, moisture over 70%, limited content of TOC, C/N ratio lower to the value recommended by the literature, and low P_{total} concentration. Furthermore, a low content of raw fiber (12.1% ± 5.2) was observed (details not included here). Raw fiber, if added, could increase C (cellulose, hemicellulose and lignin), stimulating a higher production of humic substances at the end of the composting process. The evaluation, using the matrix as a selection tool, allowed to identify two of the materials with greater potential to be used as an amendment or bulking material, that improve the quality of the substrates, due to their higher grades when applying the tool. The selected materials were bagasse and pruning waste (See Figure 2).

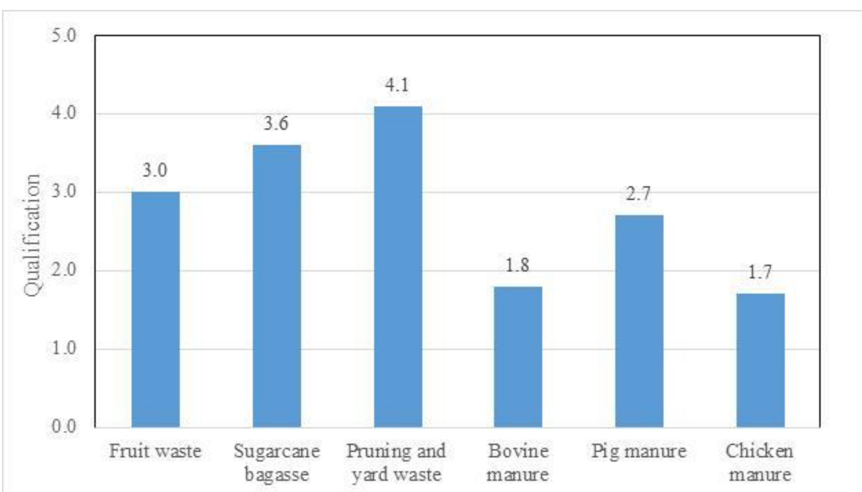

Figure 2. Evaluation of potential amendments or bulking materials in the municipality under study.

The organic substrates used as amendments or bulking materials originate mostly from vegetation sources [36]; Pruning waste, in particular, has been identified as a nitrogen source that in addition contributes to moisture regulation and improves structure and aeration [37]. Pruning waste has been successfully used in composting of food waste [38-39].

Bagasse is a lignocellulosic material composed of cellulose (50%), hemicellulose (25%) and lignin (25%) [40], which has been used in composting of bovine manure [41] or mixed with waste from the sugar industry process [42]. Bagasse is known to improve the TOC content in substrates with deficiencies in this element [12]. These materials were selected to evaluate their effect on the BW composting process.

3.4. Effect of the addition of selected amendments or bulking materials

Figures 3 and 4 present the temperature behavior during experiments 1 and 2. Generally, pile temperature had similar behavior for the same treatments (A, B, C and D). All piles, except for piles A, had a behavior typical for the composting process, with sequential phases (mesophilic < 45 °C, thermophilic > 45 °C, cooling <45 °C, and ambient temperature). Likewise, control piles (B and D) achieved the temperatures of the thermophilic range, one day later compared to the piles that had bulking materials. This finding demonstrates a positive effect of adding BM for the composting process of this kind of BW in agreement with previous reports [38-39].

The shorter time required to reach the temperatures of the thermophilic range in the piles with bulking material may be associated with an improvement in the substrate conditions: neutral pH values and higher porosity, which improve the environment for microbial metabolism. This improvement was also reflected in lower times required to reach the maximum temperatures (i.e. days 2 and 3) and in a shorter duration of the thermophilic phase (i.e. between 9 and 19 days), compared to the control piles that reached the maximum temperature between the days 11 and 18 and had a duration of the thermophilic phase between 19 and 25 days. Despite the differences found, all the experimental units fulfilled the conditions proposed by Haug [43], who stated that temperature must be maintained in the thermophilic range for at least four days to ensure hygienization.

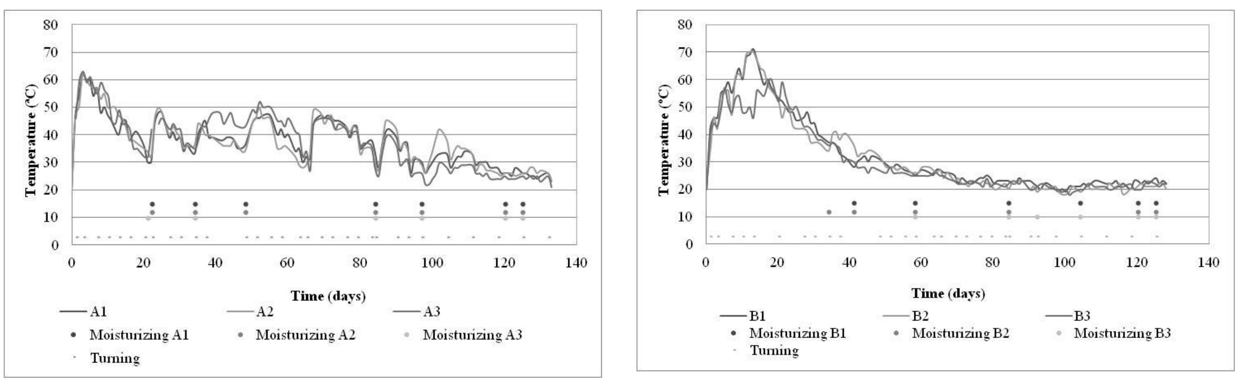

Figure 3. Temperature evolution in piles of experiment 1.

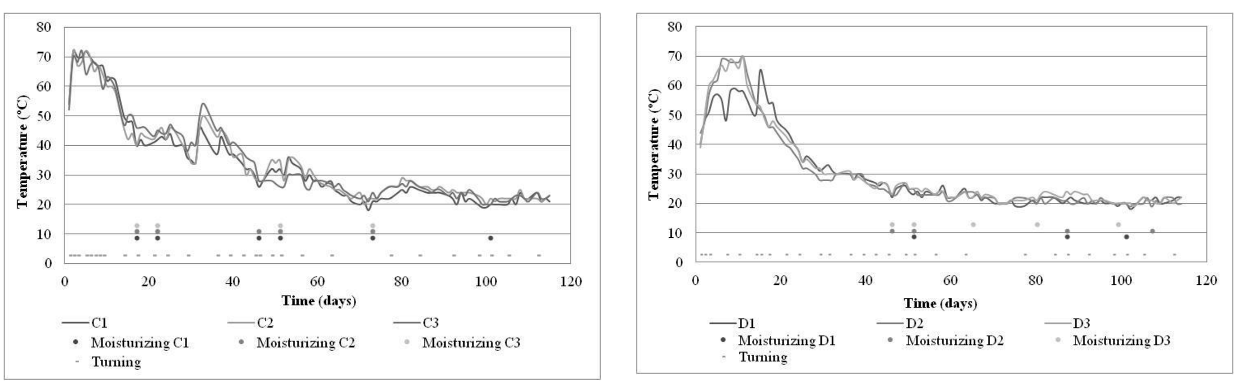

Figure 4. Temperature evolution in piles of experiment 2

Cooling and maturation phases were similar in the control piles and star grass piles (C), with a steep drop between days 20 and 50 (piles B and D), and 15 to 65 (piles C), followed by a less pronounced drop before reaching temperatures near ambient. In contrast, piles A did not have a similar process development, having continuous temperature oscillations. This fact could be associated with presence of hardly degradable compounds in SCB, which slowed and then speeded up the process in an alternate form each time the process was submitted to operation (i.e. turning and moisturizing). After the experiments finished, control piles reached temperatures close to ambient, while piles (A y C) were 2 or 3 °C above ambient temperatures.

Regarding pH, Table 3 showed that in all cases, at the beginning of the experiment, substrates from the four treatments (A, B, C and D) had values in the acidic range. The incorporation of star grass allowed to increase the pH to values close to neutral conditions. Information provided in Oviedo-Ocaña et al. [23] showed that from the second and third monitoring days, pH in the piles increased to values between neutral and alkaline, and this condition was maintained until the end of the process (see Table 7).

In relation to product quality, in experiment 1, piles from treatments A and B had statistically significant differences for four parameters (pH, N_{Total}, C/N and BD), while experiment 2 had statistically significant differences for eight parameters (pH, moisture, C/N, K_{Total}, EC, CEC, TFC, TC). As expected, bagasse improved the TOC content, bulk density (BD), WHC, GI, and reduced pH in the product. However, a decrease in nutrient content such as nitrogen and phosphorus was identified, which shows the need to add a complementary material to favor the presence of these nutrients.

Star grass also improved parameters such as TOC, pH, BD, and WHC. Adverse effects of adding this material did not occur. In general, both bulking materials increased product quality and improved fulfillment of criteria stated by the Colombian NTC.

Table 7. Quality of the obtained products in piles of the experiments 1 and 2.

Parameters	Experiment 1 Piles B	 Piles A	 p-value	Experiment 2 Piles D	 Piles C	 p-value	NTC 5167
pH	8.01 ± 0.13	7.38 ± 0.07	0	10.10 ± 0.28	9.90 ± 0.17	0.318	> 4 and <9
Moisture, % wb	39.00 ± 0.87	49.47 ± 11.14	0	32.77 ± 5.62	34.50 ± 3.29	0.714	< 35
TOC, % db	12.77 ± 1.97	17.77 ± 1.46	0	13.73 ± 0.40	18.87 ± 2.70	0	> 15
N_{Total}, % db	1.54 ± 0.51	0.90 ± 0.69	0.092	0.90 ± 0.12	2.02 ± 0.50	0	> 1
C/N	9.43 ± 5.37	28.23 ± 18.79	0.122	14.77 ± 1.89	9.67 ± 3.13	0.098	--
Ashes, % db	62.63 ± 1.93	57.23 ± 1.00	0	65.67 ± 2.28	61.03 ± 1.33	0	< 60
K_{Total}, % db	3.78 ± 0.37	3.11 ± 0.40	0	3.23 ± 0.38	3.92 ± 0.13	0.293	> 1
P_{Total}, % db	1.45 ± 0.17	1.04 ± 0.08	0	1.32 ± 0.06	1.26 ± 0.10	0	> 1
BD, g cm^{-3}	0.61 ± 0.03	0.44 ± 0.07	0	0.55 ± 0.07	0.34 ± 0.04	0	< 0.6
WHC, % wb	124.4 ± 7.1	168.83 ± 9.91	0	120.4 ± 6.9	165.6 ± 18.6	0	> 100
EC, dS m^{-1}	0.74 ± 0.23	0.43 ± 0.07	0	0.49 ± 0.07	0.49 ± 0.07	0.907	--
CEC, meq 100 g^{-1}	52.3 ± 0.9	56.2 ± 1.87	0	49.7 ± 1.56	50.0 ± 2.7	0.694	> 30
TFC, NMP g^{-1}	809.3	751.0	0.888	10.0	7.7	0.703	--
TC, NMP g^{-1}	17.0	23.0	0.814	0.0	0.0	0.903	--
Germination index, %	35	88	--	30	45	--	--

[a]Average data ± standard deviation; BD: Bulk density; WHC: water holding capacity; EC: electric conductivity; CEC: cation-exchange capacity (CEC), TC: total coliforms; TFC: total fecal coliforms
Source: Adapted from Oviedo-Ocaña et al. [23].

3.5. Prospects for future work on BW composting in developing countries

The systemic analysis of the composting performance allowed to identify strategies for the promotion of this technology in developing countries. In addition to these strategies, in the technological component, knowledge must continue to increase in elements such as: i) improvement of product quality to increase its competitiveness compared to other organic fertilizers and amendments; ii) research on mechanisms for process control and monitoring, adapted to the small-scale composting facilities; iii) selection of amendment and support materials considering multicriteria; iv) simultaneous assessment of several operational strategies in BW composting (e.g. aeration, addition of amendment or bulking materials, moisture); v) application of optimization models at laboratory or pilot scale to evaluate aspects such as degradation rates, environmental impact assessment (i.e. gases) or product quality.

4. Conclusions

The research developed has allowed a better understanding of the composting process performance in developing countries, identifying strategies that can contribute to its improvement. The quality of the biowaste composting substrates is variable, and limits the consistency in the quality of the end-product. However, the adequate selection of bulking materials improves the process and quality of the composting product and can contribute to its positioning as a biowaste management technology in developing countries.

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