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Evaluation of Techniques for the Valorization of Residual Biomass from Tomato Production within a Circular Economy Perspective

Evaluación de técnicas de valorización de la biomasa residual de la producción de tomate dentro de una perspectiva de economía circular

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ABSTRACT

The valorization of agricultural residual biomass is one of the main strategies for advancing the circular economy in the Colombian context. However, this process must consider an comprehensive vision that takes into account the potential of the waste. The purpose of this work was to evaluate three technologies for the *in situ* valorization of residues from fresh tomato production: biochar production in a retort system, composting, and co-composting. In the first phase, the residual biomass of the tomato production system was characterized, then the technologies were implemented and evaluated from an economic and life cycle approach considering the flows of materials, water, energy balance, costs, and time, in terms of functional unit of analysis of one ton of final product obtained. It was determined that for every ton of fresh tomato produced, about 297.7 kg of organic waste is generated, confirming the technical feasibility of the evaluated technologies. However, biochar—despite showing the expected temperature profile for slow pyrolysis—proved disadvantageous at small scale due to its cost and energy demand. On the other hand, the addition of biochar to compost increased nitrogen retention by 35% and reduced water requirements, while maintaining the expected characteristics. This finding highlights opportunities in the integration of technologies aimed at enhancing the use, recirculation, and valorization of agricultural waste biomass.

Keywords: Biochar; Circular agriculture; Co-composting; Organic amendments; Sustainable agriculture.

RESUMEN

La valorización de la biomasa residual agrícola es una de las principales estrategias potenciales para el alcance de la economía circular en el contexto colombiano. Sin embargo, este proceso debe considerar una visión integral teniendo en cuenta el potencial del residuo. El propósito de este trabajo fue evaluar tres tecnologías para la valorización *in situ* de residuos resultantes de la producción de tomate fresco, incluyendo biocarbón en sistema de retorta, compostaje y co-compostaje. En una primera fase se caracterizó la biomasa residual de los sistemas de producción de tomate, posteriormente se implementaron las tecnologías y se evaluaron desde un enfoque económico y de ciclo de vida considerando los flujos de materiales, agua, balance energético, costes y tiempo, en términos de unidad funcional de análisis de una tonelada de producto final obtenido. Se determinó que por cada tonelada de tomate fresco producido se generan unos 297.7 kg de residuos orgánicos, por lo que las tecnologías son técnicamente viables. Pero el biocarbón, a pesar de tener el perfil de temperatura esperado para la pirólisis lenta, no es ventajoso a pequeña escala en términos de coste y demanda energética. Sin embargo, la adición de biocarbón al compost aumentó la retención de nitrógeno en un 35%, y demandó menos agua en el proceso manteniendo las características esperadas, lo que influyó en su valorización y llevó a la conclusión de que se pueden encontrar oportunidades en la integración de tecnologías que buscan aumentar el uso de la biomasa de residuos agrícolas, su recirculación y valorización.

Palabras claves: Agricultura circular; Agricultura sostenible; Biochar; Cocompostaje; Enmiendas orgánicas.

INTRODUCTION

From the CE (Circular Economy) approach, the *in situ* use and recovery of waste are considered essential practices, as they can reduce the impacts associated with transport to treatment plants and prevent other inadequate treatment pathways (Duque-Acevedo *et al*. 2023). This decentralization of waste utilization also offers operational advantages by enabling waste management and utilization based on the principle of proximity—that is, near the point of origin—which facilitates producers' response to variations in generated quantities and reduces logistics costs in waste management (González *et al*. 2020). In addition, small-scale technologies such as composting and biochar have been shown to have better environmental performance than landfilling (Zhao *et al*. 2020).

For waste self-management to be feasible, the chosen utilization technique must consider the potential of the waste, along with its environmental, economic, and technical performance, while also addressing local demands. The different technologies for waste utilization have advantages and disadvantages related to their energy consumption, investment cost, environmental performance, yield, and compliance with CE principles. Many studies on technologies for the valorization of agricultural residues have focused on technological or environmental perspectives, while often overlooking socio-economic aspects (Duque-Acevedo *et al*. 2020; Schmidt Rivera *et al.* 2020; Viaggi, 2022). Suitable technologies for waste valorization, beyond their orientation toward environmental protection, are essential for advancing the circular economy and achieving sustainable development.

In response to this situation, the objective of this research is to evaluate and compare the performance and suitability of biochar, co-composting, and composting technologies for the *in situ* use of organic residues from tomato production under greenhouse conditions of small-scale agricultural production. This research considers technical and economic aspects, establishing the potential of each technology to be used locally within the framework of CE.

The novelty of this evaluation lies in approximating the real conditions of residual biomass utilization technologies and assessing their performance in a local context, considering that, although these technologies are not new, their viability depends on existing practices and the capacity of available infrastructure. On the other hand, no studies were identified in which the combination of biochar with compost from residues obtained exclusively from the tomato plant was evaluated, which could contribute to nitrogen retention and to the improvement of its properties (Malinowski *et al*. 2019).

This work seeks to advance waste self-management toward a bio-based circular society and the achievement of the SDGs, with greater community participation while preventing problems linked to inadequate waste disposal. Unlike most evaluations of tomato waste technologies found in the literature—which are typically conducted in laboratories or under centralized waste management conditions—this work emphasizes local, decentralized contexts.

MATERIAL AND METHODS

The evaluation of *in situ* technologies for the use of tomato production residues— specifically biochar, composting, and co-composting—was conducted between 2022 and 2023 in the municipality of Sutamarchán (Boyacá, Colombia). This municipality is characterized to produce tomato under greenhouse conditions, mainly carried out by small farmers, as its main economic activity (Alcaldía Municipal Sutamarchán, 2023). Prior to the evaluation of the technologies, the residual biomass generated during the tomato production cycle was characterized. The residual biomass was collected from three production systems with more than ten years of tomato production. A completely randomized experimental design was used to carry out a comparative evaluation between the waste utilization technologies described above, considering each one as a treatment. In addition, stratified sampling was applied across three tomato production systems, with a weekly sample size of 15 to 20 randomly selected plants in each system (Hernández Chaverri & Prado Barragán, 2018). For each selected plant, the waste generated (leaves, stems, and fruits) was quantified and weighed throughout production, as well as the total amount at the end of the cycle (Hernández Chaverri & Prado Barragán, 2018; Manríquez-Altamirano *et al.* 2021). The descriptions and evaluations for each treatment are provided in the sections below.

Biochar. The pyrolysis process was carried out according to the biochar production parameters described by Memici & Ekinci (2020) and Amalina *et al*. (2022), in relation to the preparation of the feedstock and the temperature values required to achieve slow pyrolysis. Regarding the procedures for obtaining biochar, the materials and methods described by Dunlop *et al*. (2015) were taken into account, given their similarity with the availability of resources (retort reactors as pyrolyzer, wood for combustion generation) and raw materials (agricultural residues from tomato farming) for this study. The stems of tomato plants were selected for analysis, as their woody nature and lignin content are associated with higher yields (Memici & Ekinci, 2020), cutting them in sections of between 1 and 3 cm to ease the subsequent natural drying process. To carry out pyrolysis, a retort-type reactor according with Island Blacksmith (2022) was employed.

Residual wood was used as fuel, placed both in the space between the internal and external walls of the reactor and at the base of the reactor. The temperatures reached were measured both at the external wall of the reactor using an infrared pyrometer, and inside the retort kiln using a gauge thermometer provided for this purpose.

Composting and co-composting. A closed composting system was chosen to avoid problems associated with leachate, direct sun exposure, and rain, providing a controlled environment for the process (Wainaina *et al*. 2020; Zhao *et al*. 2020). Five horizontal rotating drum bioreactors were constructed, each with a capacity of 0.22 m^3. The reactors rotate on four fixed wheels that distribute the weight and are perforated to facilitate ventilation. The waste was chopped into pieces of 1-3 cm to accelerate the degradation process, and the containers were filled to 75% of their capacity. The mixture was adjusted to a C/N ratio of 30 (Tabrika *et al.* 2021). As raw material, mainly fruits, leaves, and secondary stems (80%) were used by combining them with soil as suggested by Navia-Cuetia *et al*. (2013). Humidity was monitored weekly to maintain levels between 50% and 60%, while aeration was controlled within a range of 5% to 15%. Temperature and pH were monitored to verify that the thermophilic and mesophilic stages and the maturity of the compost developed in the process.

Since the incorporation of biochar into compost has been shown to enhance nitrogen retention and improve compost properties (Malinowski *et al.* 2019), an additional set of bioreactors was established to evaluate the co-composting process. For this purpose, a mixture of the same compound prepared for composting was combined with a portion of the biochar obtained from the residual stalks, with the aim of evaluating both the process and the quality in comparison to compost without additives. In this setup, the same parameters were used as in composting, implementing 5 horizontal rotating drum bioreactors containing chopped residues from tomato crops, as well as biochar from tomato stalk residues adapted to sizes of less than 1 cm, of which 2% was added with respect to the total weight of the mixture (Malinowski *et al*. 2019).

Studies such as that by Picca *et al*. (2023) have explored the use of co-composted biochar in tomato substrates, but there is little information on its direct effect on tomato waste composting in rotational systems. Therefore, the results of this study provide original data. It was observed that biochar improved the thermal stability and structure of the compost, in line with Oviedo-Ocaña *et al.* (2025), who reported improvements in biological activity and nutrient content. The similarity in operational parameters and the observed improvement in compost quality with biochar suggest that co-composting may be an effective strategy for agricultural waste management, especially in crops such as tomatoes, where stems represent a viable source of biomass for biochar (Llorach-Massana, *et al*. 2017; Oviedo-Ocaña *et al.* 2025).

Characterization of the quality of the obtained raw materials. Once the above processes were completed, representative samples were taken for laboratory analysis according to standard NTC 5167 (ICONTEC, 2011). The following variables were analyzed: pH by electrometry, total nitrogen by the Kjeldhal method, total potassium by atomic absorption, total phosphorus by colorimetry, oxidizable organic carbon by the Walkley-Black method and colorimetry, the presence of heavy metals such as arsenic, cadmium, chromium, mercury and lead, and water retention capacity by the volumetric method. For this study, nitrogen content was established as a variable of interest for the comparison of technologies in the fertilizer category, due to its importance in tomato production, since nitrogen availability is the main essential nutrient for tomato growth, biomass production and yield (Barzee *et al*. 2019; Ronga *et al*. 2020).

Techno-economic analysis. To compare the technologies from an EC point of view, a cost analysis and a material, water, and energy flow analysis were carried out following the ISO 14040 life cycle approach (ISO, 2006), given its wide use in environmental performance assessments in agriculture and tomato production systems (Torres Pineda *et al.* 2021; Boschiero *et al.* 2023). LCA involves collecting and evaluating the inputs and outputs at each stage of a process to analyze and identify potential environmental aspects of concern of a product throughout its life cycle (International Organization for Standardization, 2006). This methodology involves defining the study objective and scope, inventory analysis, and evaluation of the environmental aspects in order to interpret the results obtained at each stage.

In this study, the objective of the analysis is to compare the performance of the technologies. The functional unit of analysis chosen for this comparison is 1 ton of the final product obtained from tomato waste biomass (biochar, compost and co-compost), in order to incorporate the calculation of input-output balances based on the main operational data of each technique. This selection of the functional unit is based on its relevance in the agricultural sector, as it is related to the quantity of agricultural product produced, which is normally used in the sector because it is simple and easy to interpret (Torres Pineda *et al.* 2021). On the other hand, this functional unit facilitates the comparison between different technologies, as it allows to evaluate the yield per unit of product obtained and to make informed decisions.

The scope of the analysis included all activities, from waste collection and preparation to the manufacturing process and final product. In these stages, the inventory of the on-site cycle was carried out, taking into account the flow of materials, the yield, and the amount of water demanded in the process. These data were adapted to the functional unit after being collected. To quantify the energy, an energy balance (input/output) was made with information on material flows, the calorific value of each material, the time spent and the human labor hours required for the process. The energy invested in the functional unit established was determined based on the conversion factors and energy equivalence per post in Pimentel (2009).

The economic analysis was carried out using the same functional unit and scope mentioned above, identifying direct costs (cash flow), material adequacy, investment costs (containers), inputs, operation (labor, energy), and maintenance, in accordance with the references consulted in this regard (Keng *et al*. 2020). Transportation costs were not considered, since the practice of self-management, unlike other waste management methods, would represent a saving (Torrijos *et al.* 2021).

RESULTS AND DISCUSSION

Monitoring of tomato crop residues during and at the end of the production cycle revealed the generation of different types of waste, including discarded fruit from commercialization, plastics from tutoring activities, and stems and leaves. Sixty-four percent of the waste is generated during the cultivation cycle (6 to 7 months), mainly leaves and fruit, while 36% is generated at the end of the cultivation cycle, where stems are generated to a greater extent (Figure 1). It was estimated that for each ton of tomato marketed, 297.7 kg of organic residues are generated. The evaluated production systems showed yields close to 105 t/ha; in other words, each hectare generates an average of 31,258.5 kg of organic residues.

Biochar. The small-scale biochar process showed the expected temperature profile, with a total pyrolysis time of 60 minutes: 40 minutes for heating and 20 minutes for holding. Temperature data were measured on points around the retort furnace by averaging the temperatures at different time intervals (Figure 2). Maximum temperatures of approximately 460 °C were recorded with, a p-value of 0.18 at $\alpha = 0.05$, and heating rates of 0.15 °C/s. These results classify the process as slow pyrolysis, according to Memici & Ekinci (2020), since the heating rates are below 0.3 °C/s. The maximum temperature reached (460 °C) was slightly lower than that reported by these authors (≈500 °C).

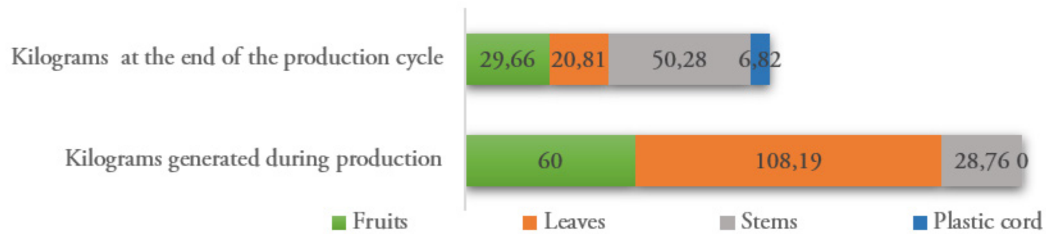

Figure 1. Waste generated in tomato production systems under greenhouses

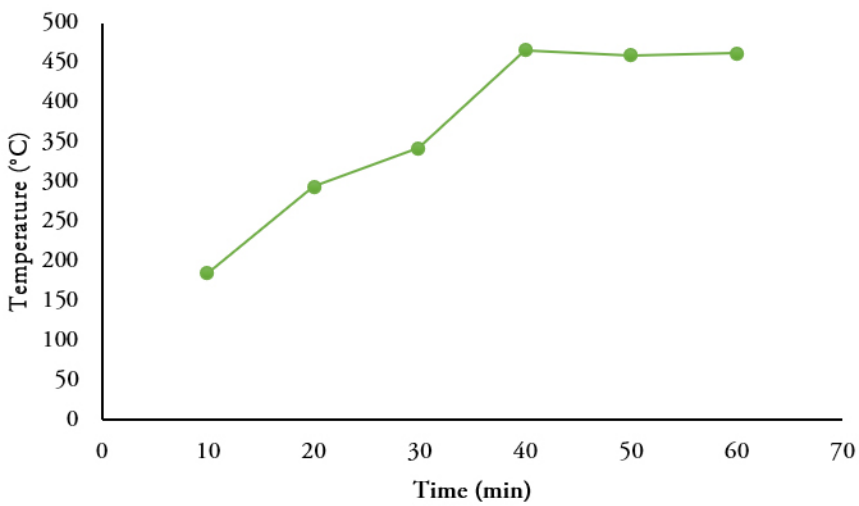

Figure 2. Temperature profile biochar as a function of time during the experimental process.

It was estimated that 3161 kg of stems is required to produce one ton of biochar, with a yield of 31.6% by weight and 49.1% by volume. These values are comparable to those reported by Altıkat *et al.* (2024), who obtained between 32.7% and 34.1%, and close to those reported by Llorach-Massana *et al.* (2017), who reported yields between 38% and 45% for tomato waste. The differences observed could be attributed to the fibrous nature of the material and the thermal efficiency of the system used.

In terms of energy, beyond the hourly human labor required for assembly and operation, it was determined that the pyrolysis of the material loaded into the prototype required approximately 8.4 kg of wood. Considering a specific heat capacity of 1700 J/kg ºC for wood, the process demanded about 6.2 MJ of energy. No previous studies were found that report specific energy consumption for pyrolysis systems of this scale and configuration, so these data could represent an original contribution for future comparisons and optimizations.

Composting and co-composting processes. The two configurations showed the expected behavior in the process, in both the mesophilic, thermophilic, and cooling phases. The temperature of the two mixtures increased rapidly in the first two days reaching values above 40 °C, the first week the temperature increased rapidly until reaching maximum values of 62 °C for composting and 58 °C for co-composting (Figure 3). The cooling phase began in week 6 when the temperature dropped below 55 °C to stabilize the process after 9 weeks. This thermal behavior partially aligns with the findings of Qu *et al.* (2022), who reported that the addition of biochar can extend the thermophilic phase and reach temperatures above 63 °C in composting with biogas residues.

Furthermore, it was not necessary to add water during the first five weeks, thanks to the high moisture content of the fruits, which represents an operational advantage over other systems that require frequent irrigation (Llorach-Massana *et al.* 2017). In the biochar treatment, there was less need for turning, attributed to the greater porosity of the material, which coincides with the findings of Oviedo-Ocaña *et al.* (2025), who highlighted that biochar improves aeration and reduces the frequency of handling in composting.

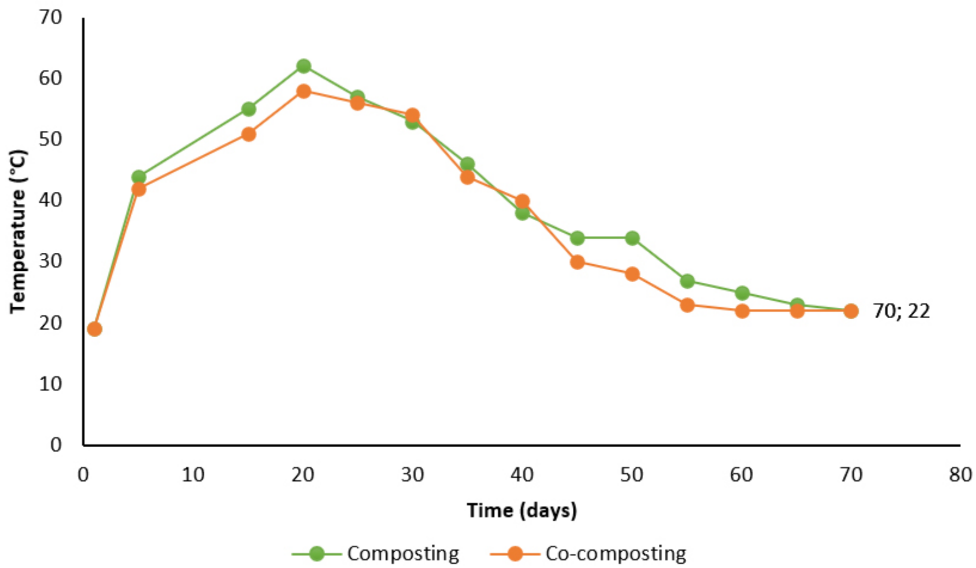

Figure 3. Temperature profile Composting and co-composting

Agrochemical quality characterization of the raw materials obtained. The characteristics evaluated for the technologies (Table 1), such as C/N, pH and heavy metal content, meet the requirements established in the regulations (Norma Técnica Colombiana NTC 5167). For composting and co-composting, the C/N ratio in both cases reached the optimum value of 15.9 for agricultural application, below the limit of 20 established in the aforementioned standard. These results are consistent with values reported in the literature for tomato waste composting at other scales and contexts; for instance, Pane *et al.* (2015) reported C/N ratios between 15 and 20 in agricultural-scale composting.

Table 1. Physicochemical analysis of the samples of biochar, compost and mixture of compost and biochar evaluated.

Parameter	Unit	Biochar	Compost	Co-compost
pH	-	10.48	6.5	6.51
C/N	-	54.4	15.9	15.9
Total nitrogen	%	0.24	0.62	0.84
Total Potasium	%	0.287	0.64	0.78
Total Phosphorous	%	0.24	0.03	0.03
Water retention capacity	%	101.66	75.7	78,4
Arsenic	mg/kg	0.05	< 0.04	< 0.04
Cadmium	mg/kg	< 0.2	< 0.2	< 0.2
Chromium	mg/kg	< 2	< 2	< 2
Mercury	mg/kg	0.34	< 0.04	< 0.04
Lead	mg/kg	3.13	< 2	< 2

For composting and co-composting, pH values obtained are in the range between 6 and 7, which also meets the regulations (Norma Técnica Colombiana NTC 5167). Regarding pH, the value of 10.48 obtained in the biochar is consistent with that reported by Memici & Ekinci (2020), who found values between 9.5 and 10.6 in biochar produced from plant residues. This confirms the suitability of biochar as a soil amendment for acidity correction. It was found to have high moisture, phosphorus, and potassium retention capacity, although to a lesser extent than the other technologies. A C/N ratio of 54.4 was also obtained, indicating a higher proportion of carbon typical of pyrolyzed materials, which can enhance compost stability when used as a soil amendment.

The cation exchange capacity (CEC) obtained for the compost met the expected standards (>30), with values of 47.9 meq/100 g for compost and 43.3 meq/100 g for co-compost. The lower value in the latter is attributed to the addition of biochar, which is consistent with the findings of Antonangelo *et al.* (2024), who note that the type of biochar and its ash content can significantly influence the soil's CEC.

Regarding nitrogen and potassium, co-composting showed values 35% higher in nitrogen and 22% higher in potassium compared to composting. It is worth noting that nitrogen is one of the key parameters used to determine the quality and suitability of products for fertilization or soil amendment. Results delivered by external laboratories report that the highest concentration of total nitrogen was for co-composting with 0.84%, compared to 0.62% for compost and 0.24 % for biochar. This indicates that the addition of 2% biochar to the co-composting mixture had a positive effect on nitrogen retention, consistent with Agyarko-Mintah *et al.* (2017), who demonstrated that incorporating biochar into compost enhances nitrogen retention and the availability of essential nutrients. Biochar does not contain significant amounts of nutrients and, on its own, would not serve as a nutrient source or alternative to chemical fertilizer. However, when applied to compost, it retained nitrates and water, due to its pH characteristics, can also be used as an amendment in acidic soils.

Both samples showed organic carbon values below the standard (15%), and the biochar incorporated in the compost also improved aeration due to its porous structure and water retention capacity (Table 1). This is consistent with findings reported in studies such as that by Mikajlo *et al.* (2024), who found that composting with biochar improves porosity and water retention capacity, especially in low-fertility soils.

The quality achieved with residues from the production systems themselves—particularly in co-composting with respect to nitrogen—represents a technically viable option, as it increases the recirculation of on-site resources and aligns with CE principles. This addition also led to greater water retention, meaning a lower water demand in the process, which is important in the study area.

Techno-economic analysis. The energy concerns in this work include the construction, operation, and disposal for the composting, biochar and co-composting processes. As shown in Figure 4, biochar is the process with the highest energy demand per functional unit, requiring approximately 5,400 MJ for the pyrolysis of dried tomato stem waste. This value is intermediate within the range reported by Joseph et al. (2021), who noted energy demands of 5,000–6,000 MJ for similar processes, depending on the type of biomass and pyrolysis conditions. In comparison, Wilson & Miles (2020) report values close to 4800 MJ in composting systems with biochar integration, suggesting that the result obtained in this study is slightly higher, possibly due to the low energy density of the waste used and the absence of heat recovery in the system evaluated. It is also the only valorization pathway where the processing of inputs demands a different type of energy than that generated by human labor, resulting in the costs associated with the production of biochar.

Human labor has a high incidence in the transformation of tomato waste across all the valorization pathways evaluated. Biochar once again showed the highest requirement, at 1871 MJ, followed by composting and co-composting, which had similar human labor energy demands of approximately 75.55 MJ. These results contrast with those of Weldon *et al.* (2023), who report that adding biochar to compost does not significantly increase the demand for human labor. It is worth noting that approximately 70% of the labor is required for tomato waste preparation compared to the effort dedicated to the operation and maintenance of the composters. This highlights an opportunity to improve the energy requirements of the valorization pathways analyzed in this study.

The high incidence of human labor in energy requirements is primarily due to the small-scale framework of analysis of this project, where labor predominates in the absence of large-scale infrastructure for tomato waste transformation processes. It should also be noted that the energy associated with the transportation and/or handling of tomato waste for processing to and from a treatment plant is not included in each of the valorization strategies, given that the aim is to provide alternatives for self-consumption by the producer, avoiding costs and environmental problems.

Moisture is a critical factor in the composting process, as water retention and demand can be conditioned by the substrate and environmental conditions of the composting site (FAO, 2013).Therefore, in the closed horizontal rotary drum bioreactors, moisture was monitored to ensure that it was not affected by conditions such as rain, wind flow fluctuations and leaching (Rashwan *et al.* 2021) to maintain a moisture content between 50% and 60% during the active period of composting.

Constant monitoring of water demand revealed an advantage associated with the moisture content of tomato plant residues (Figure 4), particularly from the use of discarded fruits, which reduced the need for water addition during the first month in both composting and co-composting. This finding is consistent with that reported by Le Guyader *et al.* (2024), who demonstrated that plant residues with high moisture content can significantly reduce water demand in composting processes in arid areas. This represents an important consideration in waste recovery, as it reduces costs by utilizing an *in situ* resource and optimizes a critical resource in water-scarce areas, such as Sutamarchán.

Another important finding is related to the integration of technologies. When comparing water demand in composting with co-composting (Figure 4), it was found that co-composting demanded 9 % less water, associated with the characteristics of the added biochar, such as its porosity and high-water retention rate. This can be an advantage in dry areas, in addition to leachate retention (Purakayastha *et al.* 2019; Guo, 2020).

The evaluated technology in this study enables water recirculation and reduces water demand during waste recovery processes. Although the volume of water involved may seem minor compared to other energy resources or materials, its consumption has been scarcely addressed in evaluations of waste recovery technologies. Some authors, such as Torrijos *et al.* (2021), argue that the cost of water is not significant in these processes, which may explain why water use has not been highlighted as a critical variable in the literature on tomato waste (Navia-Cuetia *et al*. 2013; Agyarko-Mintah *et al*. 2017; Malinowski *et al*. 2019; Rashwan *et al*. 2021; Tabrika *et al*. 2021).

However, recent studies have begun to highlight the importance of water in the tomato industry. Efficient water use and conservation are key principles of the CE, designating water as a strategic resource to be optimized and recirculated.

Costs. Table 2 summarizes the costs associated with each technology, scaled to the functional unit and evaluated under the *in situ* conditions faced by small farmers. These costs depend on the country's economic context, which influences factors such as valuation and inflation (Ramos & Rouboa, 2020).

Composting and co-composting show positive net results, meaning the use of these residues generates economic benefits, unlike biochar, where costs exceeded revenues.

The most cost-effective technology turned out to be composting, due to its low operating costs and the advantage of reducing the time and effort required for turning due to the rotating system of the bioreactor used. Another advantage of composting is that it takes 10 weeks, which would facilitate its use in a short period of time. In contrast, biochar requires stalk drying times of about 1 week. In addition, co-composting costs 14% more than composting due to the incorporation of biochar considered as an enriching input, however, better characteristics lead to a better price and nitrogen retention leads to a higher value of the fertilizer as a product (Agyarko-Mintah *et al.* 2017), so a higher profit is obtained as a result of the balance. Labor was the most expensive component in the case of biochar production exceeding 90% of the costs, especially due to labor demand to adapt the stems in short times. This causes that in comparison with compost, the production of biochar can be up to 20 times more expensive.

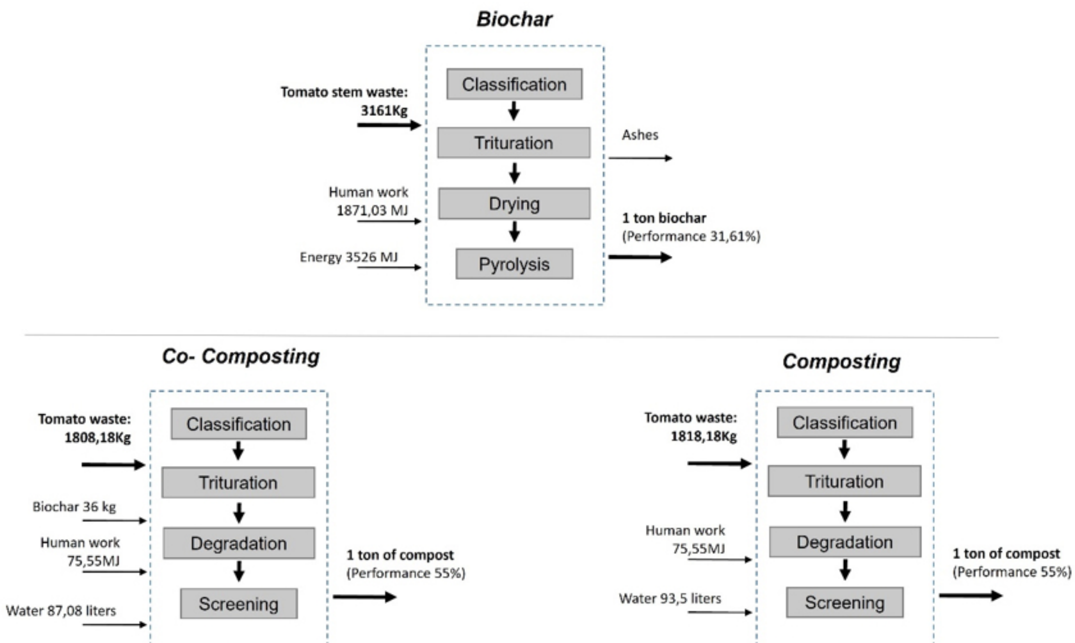

Figure 4. Summary of the processes carried out in each assessed technology.

Table 2. Costs and incomes for each ton of product

Costs and incomes	Biochar		Compost		Co-compost	
	COP$/ ton	%	COP$/ ton	%	COP$/ ton	%
Staff (assembly and operation)	860.7128,99	90	353.643,136	81	353.643,14	71
Energy	328.654,48	3	0	0	0	0
Materials and supplies	652.868,832	7	84.500,42	19	154.978,21	31
Total costs	9.588.652,30	100	438.144,784	100	500.056,48	100
Incomes	3.850.000	-	1.047.200	-	126.2800	-
Net balance	-5.738.652,304	-	609.055,216	-	762.743,52	-

From a waste valorization perspective, compost and biochar are products that farmers can either use or sell locally. From a cost perspective, one of the most important strategies to maximize process profitability is reducing the amount and cost of personnel required for operations, particularly in waste preparation (Alege *et al.* 2021). The development of technologies for shredding and separation of waste *in situ* are required, in addition to the need to replace the tutoring rope with biodegradable alternatives, so that they can be used in the composting and biochar process, reducing the time and cost of processing tomato crop residues, in addition to the obvious environmental problems.

Although, in the literature there are few evaluations for the costs of using organic waste *in situ*, in which the costs obtained for composting and co-composting processes are much lower than those reported in evaluations for the decentralized use of organic waste (Keng *et al*. 2020; Torrijos *et al*. 2021). This is because these technologies are built by the farmer using locally available resources, aiming to reduce the costs of transporting and disposing waste.

However, to improve the quality of the product for agricultural use, greater nitrogen retention is essential, which implies a higher cost–benefit ratio. In this regard, biochar production from the same tomato waste is advantageous, particularly since stems—generated in the largest quantity at the end of the production cycle—can be partially used for its production. The combination of biochar and compost increases the efficiency of the process, also providing environmental benefits such as the reduction of nitrogen loss, which would imply less emissions (Agyarko-Mintah *et al.* 2017), and a lower water demand in the process, avoiding soil contamination (Simansky *et al*. 2018). However, because biochar production requires more time and an energy source, which increases costs, it is advisable for farmers to produce only the amount needed to enhance the composting process, unless an alternative is found to optimize time, particularly for residue preparation and crushing.

The technologies evaluated showed characteristics that validate them as a way of using the resources available *in situ*. However, to improve the quality of the compost to enhance its use as fertilizer, it is important to add to the mixture other residues available to the farmer for enrichment. It is necessary to evaluate alternative materials for tutoring, since this is one of the most time-consuming activities and directly influences operating costs, in addition to the fact that the quality of the product obtained is conditioned by the quality of the separation at the source (Bruni *et al*. 2020). It is also necessary to search for alternatives that optimize and facilitate waste shredding, since this is the most time-consuming activity in waste conditioning, resulting in costs and energy in other words, consistently with other authors who have evaluated composting processes (Oviedo-Ocaña *et al*. 2023).

In conclusion, it was estimated that for every ton of fresh tomatoes commercialized, about 297.7 kg of organic waste is generated, which validates the technical feasibility of these technologies. Although the technical feasibility of on-site biochar production was established, it is not profitable in terms of cost and energy demand, requiring 3,161 kg of stems to produce one ton of biochar and consuming around 5,400 MJ of energy per functional unit, in addition to the labor costs required for stem adaptation. In contrast, its integration into co-composting proved to be more promising: the addition of biochar to compost increased nitrogen retention by 35% and required 9% less water in the process, maintaining the expected quality characteristics such as pH values (between 6 and 7), a C/N ratio of 15.9, and a higher concentration of total nitrogen (0.84%) and potassium (0.78%) compared to compost (0.62% and 0.64%, respectively).

More broadly, the results show how important it is to use multiple technologies to maximize agricultural waste valorization and resource reuse within a circular economy (CE). This approach benefits farmers by improving waste management, reducing disposal problems, and minimizing transportation costs. However, there remains room for improvement, such as optimizing times and reducing costs.

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