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Organic amendments from agro-industrial waste: Opportunities and threats for the horticulture field

Enmiendas orgánicas a partir de residuos agroindustriales: Oportunidades y amenazas para el sector hortícola

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Organic amendments production from fruit and vegetable waste (1), compost (2), hydrochar (3), and biochar (4, 5).

Photos: R. González-Forero

ABSTRACT

This review and reflection paper presents the importance of organic amendments (OA) from agro-industrial waste, such as compost, biochar, or hydrochar, due to their increasing use in the horticulture field, as an organic nutrient source and the circular economy application. However, its production is not controlled by the environmental authorities in countries of Latin America, such as Colombia, and there is no obligation to make a quality control analysis of these materials once they are ready to be released onto the market. As the main source of these materials is urban solid waste, the first part of the paper introduces how its management is, placing emphasis on the opportunity to strengthen its production and use as soil amendments in the agricultural sector. The second part of the document shows briefly how the production of the most common OA, such as compost, biochar, or hydrochar is, and some physicochemical analysis of them, from different sources. This provides evidence of the variability of these materials even more when they are commercialized as the same thing. In the final section, some recommendations for the horticulture sector are described, especially in the use of OA, as well as a sustainable and portable small-scale reactor to produce some OA in local communities, using agricultural waste. An alternative that combines environmental, economic, and sustainability benefits for the rural population. Methodologically, there were different sources of information due to the application's increasing novelty in Latin America. First, institutional/public information-related regulation of OAs is the most confident source on this topic. Secondly, scientific papers and chemical analyses of different commercial OAs were checked to demonstrate the threats of their use in horticulture. In this way, the document gives a broad perspective on the use of this kind of material to the farmers, to make the best production decisions.

Additional key words: waste recycling; soil amendments; compost; biochar; hydrochar; circular economy.

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RESUMEN

Este documento de revisión y reflexión presenta la importancia de las enmiendas orgánicas (AO) provenientes de residuos agroindustriales, como el compost, el biocarbón o el hidrocarbón, debido a su creciente uso en el campo de la horticultura, como fuente de nutrientes orgánicos y su aplicación en la economía circular. Sin embargo, su producción no está controlada por las autoridades ambientales en países de Latinoamérica, como Colombia, y no existe obligación de realizar un análisis de control de calidad de estos materiales una vez que están listos para ser liberados al mercado. Como la principal fuente de estos materiales son los residuos sólidos urbanos, la primera parte del documento introduce cómo es su gestión, haciendo énfasis en la oportunidad de fortalecer su producción y uso como enmiendas de suelo en el sector agrícola. La segunda parte del documento muestra brevemente cómo es la producción de las AO más comunes, como el compost, el biocarbón o el hidrocarbón, y algunos análisis fisicoquímicos de las mismas, a partir de diferentes fuentes. Esto proporciona evidencia de la variabilidad de estos materiales aún más cuando se comercializan como lo mismo. En la sección final, se describen algunas recomendaciones para el sector hortícola, especialmente en el uso de AO, así como un reactor sostenible y portátil a pequeña escala para producir AO en comunidades locales, utilizando residuos agrícolas. Una alternativa que combina beneficios ambientales, económicos y de sostenibilidad para la población rural. Metodológicamente, se utilizaron diferentes fuentes de información, debido a la creciente novedad de la aplicación en América Latina. En primer lugar, la regulación institucional/pública relacionada con la información de los AO es la fuente más confiable sobre este tema. En segundo lugar, se revisaron artículos científicos y análisis químicos de diferentes AO comerciales para demostrar las amenazas de su uso en horticultura. De esta manera, el documento brinda a los agricultores una perspectiva amplia sobre el uso de este tipo de material, para que puedan tomar las mejores decisiones de producción.

Palabras clave adicionales: reciclaje de residuos; enmiendas del suelo; compost; biochar; hidrochar; economía circular.

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ORGANIC URBAN WASTE AS SOIL AMENDMENT IN THE AGRICULTURAL SECTOR

The use of fertilizers, especially the organic ones, as compost, biochar, and hydrochar changed especially right after the beginning of the war between Ukraine and Russia in 2022. Ukrainian exports stopped access to fertilizers and limited the agricultural supplies (Ben Hassen and El Bilali, 2022). Only in Latin American countries was there a shortage of 70% of these chemical inputs (Forbes, 2022). This generated the search for alternatives with local materials, and the composting industry and other amendments such as biochar and hydrochar began to grow significantly in the agricultural field. The most common production of these amendments was to transform the urban organic solid waste. It also increased the application of the circular economy principles and moved on to sustainable actions in many countries. According to Fonseca (2023), more than 2,010 million tons of solid waste are generated in the world per year, of which 44% correspond to organic food. Kaza *et al*. (2021) reported that approximately 70% of this waste is disposed of in landfills, 19% is recycled, and 11% is used for energy recovery, indicating an overall low level of material utilization. In Latin America and the Caribbean, the current organic waste is around 52% of the solid waste (Correal and Rihm, 2022), but its use does not exceed 20% of the total, with questionable environmental and sanitary disposal management (Sáez and Urdaneta, 2014). This management of organic waste has acquired significant relevance, and composting has been consolidated as an effective technique to transform solid organic waste into high-quality amendments (Alvarado and Rangel, 2021), improving soil fertility and contributing to the circular economy (Valderde, 2024). In addition, as they are a considerable proportion of urban solid waste (Najar Marín, 2024), in some countries in the region, composting programs have been adopted at the community and municipal level, promoting citizen participation and waste control (Tagle-Zamora *et al*., 2025). An example of that is the case of the city of León-Mexico, where domestic composting initiatives have been developed that seek to improve waste management and promote sustainable agriculture (Tagle-Zamora *et al*., 2025). Similarly, the FAO Regional Office has been promoting compost production at the family and small-scale agriculture level for several decades, through learning guides (Román *et al*., 2013). The agricultural industry is the economic sector that generates the largest amount of organic waste in Latin America, and the disposal of this waste represents a problem since it is not used. This organic waste originates from the loss of food throughout the agricultural system; generated by inadequate harvest times, climatic conditions, inappropriate harvesting or product handling practices, and difficulties related to food marketing (Pinto-Altamiranda *et al*., 2022). This shows opportunities and threats, the first ones because organic materials are more than half of the total, with millions of tons available to use right now. In addition, they are a great nutrient source due to their organic compounds, which can be transformed into soil amendments. On the other hand, the threats include low efficiency production plants, insufficiency in regulations, low or no control on the production by the environmental authorities, and artisanal generation of the material. All this is mainly in Latin America and affects the agricultural sector, which is the main consumer of these kinds of products. Composting is the most common method used to produce organic amendments from agro-industrial waste, followed by biochar production. Hydrochar production has emerged more recently. This is expanding because, as we mentioned in the first part, urban waste management has found in these products a sustainable solution that is increasingly being used by the agriculture sector (Cao *et al*., 2023), and producers are following new, fast, cheap, and highly efficient ways to produce them.

ORGANIC AMENDMENT PRODUCTION AND PRODUCT QUALITY

Compost is the main organic amendment produced. It should be remembered that composting is a biological process of organic waste degradation that occurs in four successive stages: mesophilic, thermophilic, cooling, and maturation, reaching temperatures above 60°C (Fig. 1). During this aerobic process, microorganisms decompose organic matter, giving rise to a stable and pathogen-free byproduct, suitable for application in soils. In addition, compounds such as carbon dioxide (CO_2), water vapor (H_2O), nitrates (NO_3^-), and sulfates (SO_4^{2-}) are generated (Parra-Orobio *et al*., 2023).

Compost is distinguished by its content of stabilized organic matter, compatible with plant growth and with a partial degree of humification (Oviedo-Ocaña *et al*., 2019). Their physicochemical properties determine both their characteristics and their potential applications and include cation exchange capacity, water holding capacity, total organic carbon, electrical conductivity, bulk density, moisture, total nitrogen, inorganic nitrogen, macro and micronutrient concentration, pH, and particle size. Production consists of making 1.5-m-high piles of organic waste and turning them periodically to allow the material to aerate. The process is very simple since it basically requires the disposal area and pH and humidity control, so that aerobic microorganisms can carry out the phases described above. The raw material is mainly urban waste, as residues of fruits and vegetables; however, this material is not clean and generally is mixed with packaging waste as plastics.

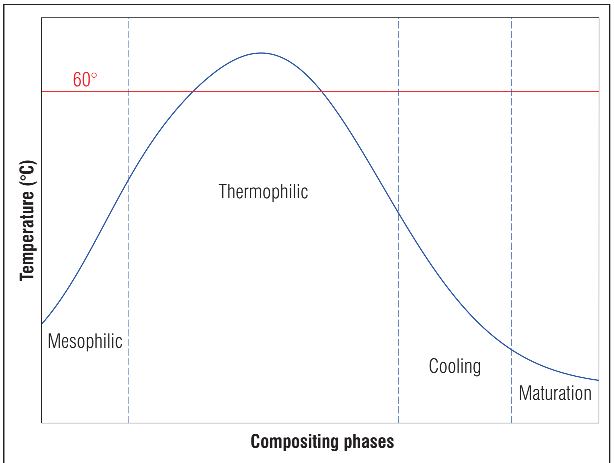

Figure 1. Composting phases among temperatures.

In addition, in this production, a common practice is the mix of urban organic waste with other materials such as wood, decomposed food products, and waste from both animal and vegetable food production industries and domestic wastewater and sludge of wastewater treatment. This makes the production process variable, and at the same time, produces the product. This is a threat in the compost production area because it requires strict quality control in the raw materials to prevent undesirable properties of the product. Unfortunately, the authorities' control is weak or non-existent, putting agricultural production at risk. It is necessary to pay attention to this situation.

To prove this hypothesis. Some compost samples were collected from different sources: La Salle University, an urban garden, goat fecal matter, and three industrial composts (obtained in the supermarket), and on them, some mandatory physicochemical tests were carried out. The tests were made at La Salle University, Bogotá campus, between June 2022 and June 2024, and compared with the regulation, obtaining the following results.

Results presented in table 1 show a high variability depending on the source of compost (fruits, vegetables, fecal material, and industrial). They were compared with the Colombian Technical Standard NTC 5167 (ICONTEC, 2022) - Organic products used as fertilizers, soil amendments, or conditioners, and recommendations of Román *et al*. (2013). They indicate high nitrogen contents in the Urban Garden, Goat Fecal Matter, and Industrial Compost 1, low contents of organic matter in almost all samples, as well as the phosphorus, on the other hand, heavy metals, such as chromium and lead, where found in industrial compost 3, which are higher than those recommended by the regulation. This has highlighted a problem, which is that there is no analysis of these materials once they are released onto the market. There is also no control over the production of these materials. Those in charge of processing state that they ask their clients about the quality of their waste, but this is not verified. This is true for industrial companies, but there is no control point for informal companies. In Colombia, the Colombian Agricultural Institute regulates production through Resolution 068370 of 2020 (ICA, 2020), which specifies as a requirement a registration of the product with the absence of *Salmonella*, total coliforms, and helminth eggs, as well as guaranteeing a minimum of 20% oxidizable organic carbon content and certain concentrations of heavy metals like those of NTC5167 (ICONTEC, 2022). The problem of using livestock waste for direct application to the soil is related to the presence of pathogenic microorganisms, methane emissions and eutrophication of groundwater; the use of biochar and hydrochar (hydrothermal carbonization) of these wastes are part of a solution that can reduce up to 97% of CO_2 emissions, as the main ecosystem benefit, and in turn, by becoming organic amendments, they increase crop yields, since they prevent the loss of phosphorus and nitrogen. The use of these processes has been identified technology against climate change (Universidad Politécnica de Madrid, 2019). Practice indicates that this requirement is to obtain the permit, not permanently, and only for those who sell, not for small ones such as urban gardens. This implies a threat to consumers and a request for the control of entities to carry out a periodic review, and the requirement of periodic laboratory analysis for these producers.

Due to the inconveniences of composting as a production process, and its challenges associated with the low degradability of lignocellulosic substances (Komilis and Ham, 2003), because the residual organic fraction of agricultural processes is characterized by a predominance of lignocellulosic matter that can range between 30 and 55% cellulose, 10% to 55% hemicellulose, and 3% to 25% lignin on a dry basis (Langsdorf *et al*., 2021), and requires a long time to degrade in nature (Begum *et al*., 2024). It makes it commercially unattractive (Teacă *et al*., 2023), the biotechnological process for the degradation and revalorization of the organic waste (Wei *et al*., 2000) if it is not operated and controlled properly, in terms of oxygen requirements, humidity, bacterial consortia, and nutrients; is slow, exceeding 200 days of operation, requiring extensive treatment areas (Teacă *et al*., 2023); generating offensive odors (López *et al*., 2002); and producing a low-quality product. That´s why it has been essential to implement technologies based on the biological carbon cycle, faster than compost, which eliminate undesirable pathogens, and contribute to the carbon neutralization process. This objective can be achieved with the production processes of biochar and hydrochar from organic waste, being part of a technological solution responsible for the removal of carbon dioxide, as an innovative and sustainable part of the current climate crisis. The products generated have the potential to mitigate climate change, improve soil quality, increase agricultural productivity, take advantage of waste and produce energy; generate synergies with agricultural and forestry activities; improve the economy and environmental sustainability (The Next 150, 2024).

Biochar or carbon-rich biochar is obtained from the decomposition of organic waste through a process of thermochemical carbonization of biomass, pyrolysis, and gasification, which consists of heating biomass

Table. 1. Physicochemical analysis of various sources of compost.

Analysis	University compost	Urban garden compost	Goat fecal matter compost	Industrial compost 1	Industrial compost 2	Industrial compost 3	Minimum value (NTC 5167: 2022)	Minimum value (Román *et al*., 2013)
pH	7.07	8.5	8.16	ND	7.32	ND	4-9	6.5-8.5
Total nitrogen -percentage (% N)	0.73	8.4	6	9.7	1.55	1.32	>1%	0.3-1.5
Organic matter (% OM)	14.1	17.4	20.7	ND	12.5	6.13	>20	>20%
Phosphorous (g kg)	0.02	0.15	0.015	0.07	0.004	ND	NA	0.1-1
CEC (cmol kg)	28.59	54.4	35.9	32.8	11.69	ND	>30	NA
Cr ($mg\ kg^{-1}$ dry soil)						1237.1	1200	
Pb ($mg\ kg^{-1}$ dry soil)						188.2	20	
Cd ($mg\ kg^{-1}$ dry soil)					1.64		39	
Cu ($mg\ kg^{-1}$ dry soil)					479		NA	

Source: González (2024) - Gray values mean not accomplishing the regulation: NTC 5167 (ICONTEC, 2022) and Román *et al*. (2013).

at high temperatures in an environment with little oxygen; under control of certain variables such as temperature, heating rate, reaction time, and biomass used. Hydrochar, on the other hand, is a carbon-rich solid material obtained from the hydrothermal carbonization of wet biomass. This process includes hydrolysis, dehydration, decarboxylation, condensation polymerization, and aromatization reactions, under a variable temperature of 180 to 350°C (Cavali *et al*., 2022). Some raw materials to produce biochar and hydrochar in Latin America correspond to agricultural waste such as crop residues, by-products of the agroindustry, manure from livestock production systems, and forestry waste such as tree biomass, paper waste, branches, trunks, and other waste from the timber industry (Pérez-Cabrera *et al*., 2021).

To produce biochar and hydrochar, some thermochemical technologies are carried out, such as pyrolysis, which is classified as slow, fast, and ultra-fast; gasification and hydrothermal carbonization, requiring biomass or waste as raw material, as stated in previous sections (Pinto-Altamiranda *et al*., 2022). From the slow pyrolysis technique, biochar and syngas are obtained, while fast pyrolysis produces bio-oil and liquids. For gasification, syngas and biochar are generated in small quantities; and finally, through the hydrothermal carbonization system, biochar and syngas are obtained (Pinto-Altamiranda *et al*., 2022). Some benefits generated by biochar and hydrochar processes are related to the increase in crop productivity with the use of their final product, the use of organic waste, the reduction of environmental impact, generating added value to the waste once transformed, carbon sequestering agents, and the reduction of CO_2 emissions; contributing to the mitigation of climate change on a small scale (Bejarano Moreno and Aguilar Díaz, 2018; Chew *et al*., 2022). Application of this technique was made in Peru, where some researchers made a production and chemical characterization of biochar from organic poultry waste in intensive poultry production systems. Chicken manure and poultry litter were used because these products were generating negative impacts on the environment, but they had high nutrient content. They made biochar and the most significant results obtained were the increase of the germination rate and growth of seedling stems of radishes when the material was applied (Trujillo *et al*., 2019), similar results obtained Muñoz-Valeriano *et al*. (2020), Chaparro (2024), Mendoza and Llorente (2022) and Ruiz (2022). Improving soil physicochemical characteristics such as nitrogen, phosphorus, potassium, and calcium, as well as an increase in organic matter and carbon in all treatments compared to the initial soil sample, and improved the crop, especially the nursery, germination, and seedbed phases. Another application of these organic amendments is carbon sequestration. Guerra (2015) demonstrated how using biochar from agroforestry crops such as sacha inchi shell and palm heart was highly effective. Advantages of this material derive from the homogeneity of the product obtained rather than the compost variability.

In a similar way to compost, some physicochemical analyses to biochar and hydrochar samples from different sources. Tests were made at La Salle University, Bogotá campus, between June 2022 and June 2024 (Tab. 2).

In this case, the results were very promising; homogeneity can be reached and adjusted from the production process in a short period of time. As this kind of production is made by single residues, physicochemical analysis depends on the waste used. Table 2 shows that the orange cascara hydrochar and bran biochar have high levels of nitrogen and low levels of CEC, which can be fixed by mixing them with other materials with low content like cocoa cascara. This is another advantage because the material permits its easy mixing with other similar products. An interesting fact was that in almost all cases, the phosphorus was low. The mixture of waste could generate very good options for regulatory compliance, but more tests are needed to apply to the final product to prepare the best options for farmers.

RECOMMENDATIONS FOR THE HORTICULTURE SECTOR IN LOCAL COMMUNITIES USING SMALL-SCALE AGRICULTURAL WASTE

The information presented in this document shows how organic amendments are an excellent opportunity in the agricultural sector because it is a natural source of nutrients, help to reduce the volume of waste in the landfills, and can capture carbon, mitigating climate change (European Union, nd). However, they must be regulated to ensure high-quality production and products that meet farmers' needs. The local horticulture sector is the most affected using these products, because it is the main consumer, especially in countries as Colombia, as the Ministry de Agriculture (MinAgricultura, 2019) indicates in its national report. To help the sector achieve maximum benefits, several recommendations are proposed to local communities, as they are most exposed to these threats.

Compost is the cheapest option for farmers to get nutrients from an organic amendment. They can look for quality products, to do that, training done by local producers, visits to organic farms, and talks with authorities can be achieved to get adequate information; as well as get support from universities and research centers about production processes and products.

Incorporating co-substrates in the composting of biowaste has proven to be an effective strategy to reduce processing time. Another interesting strategy is the addition of food waste, which favors a rapid transition to the thermophilic phase, allowing optimal temperatures to be reached in less time and accelerating the degradation of organic matter. In the study by Hernández-Gómez *et al*., 2021. In addition, biochar added to compost has shown high potential as an additive in the degradation of organic matter, since its porous structure and high cation exchange capacity increased the biodegradation rate and humification of organic material (Awasthi *et al*., 2020). Also, the addition of microbial inoculant accelerates the degradation of organic matter, significantly reduces composting time, and optimizes the physicochemical properties of the final product (Soto-Paz *et al*., 2020). To local producers, it is recommended that they look for previous research carried out by some authors such as Hernández-Gómez *et al*., 2021; Oviedo-Ocaña *et al*., 2019; Oviedo-Ocaña *et al*., 2023; Parra-Orobio *et al*., 2023, which are the basis for the

Table. 2. Physicochemical analysis of various biochar-hydrochar sources.

Analysis	Cocoa cascara hydrochar	Orange cascara hydrochar	Mango cascara biochar	Coffee waste biochar	Grass waste biochar	Bran biochar	Minimum value (NTC 5167: 2022)	Minimum vale (Román *et al*., 2013)
pH	7.06	7.23	ND	ND	ND	ND	4-9	6.5-8.5
Total nitrogen -percentage (% N)	0.75	7.26	1.15	1.45	1.05	2.17	>1%	0.3-1.5
Organic matter (% MO)	60	32.2	45.61	12.96	6.42	22.64	>20	>20%
Phosphorous (g kg^{-1})	0.14	0.022	0.02	0.05	0.12	0.1	NA	0.1-1
CEC (cmol kg^{-1})	ND	11.08	48.63	38.15	155.43	15	>30	NA

Source: González (2024) - Gray values mean not accomplishing the regulation.

implementation of modifications in the process and the successful improvement of quality products.

Considering that biochar and hydrochar are excellent options for soil improvement and carbon capture effects, a portable reactor is an option, because the farmer can generate their organic amendments. Production is fast, simple, and generates support material and nutrients for the soil. There are different technologies and techniques for the production of biochar (Su *et al*., 2022) and hydrochar (Wilk *et al*., 2024), however, most of the designs are conceived for fixed work stations, limiting the possibility of applying this solution in areas of difficult access or where due to its particular characteristics it is expensive to collect and transport the organic material to the point of transformation of this raw material. As a practical solution for local horticulture farmers, the design proposed by Obando (2015) was adopted as a starting point. This design includes modifications to a domestic microwave oven for pyrolysis applications at temperatures ranging from 450 to 600 °C, with a maximum power demand of approximately 1.4 kW. This option is cheap, sustainable, and achievable by farmers. The following explains their parts and functions.

In the literature, several applications can be found using this appliance for applications with organic waste, such as the one presented by Foong *et al*. (2024) or by Qiu *et al*. (2024), showing that pyrolysis with the help of the microwave oven is energy efficient compared to an electrical resistance system. Also, to design the electrical energy storage system that will supply the power required for combustion for a given time, it is established that the microwave can operate continuously for up to 30 min, according to the times presented by Dhyani and Bhaskar (2018) for intermediate pyrolysis. This system is, in principle, like any on-grid solar installation (Fig. 2); however, it is important to highlight some particularities that deserve attention.

The first thing to be observed is that the proposed system consists of two subsystems, one fixed and one portable. The first consists of obtaining electricity through a power source, preferably sustainable or of minimum impact, but also considers the possibility of acquiring the required power through a domestic network or auxiliary generators. The second consists of a constant supply system, composed of a charge controller, a battery bank, a power inverter, and the reactor using a modified domestic microwave. The

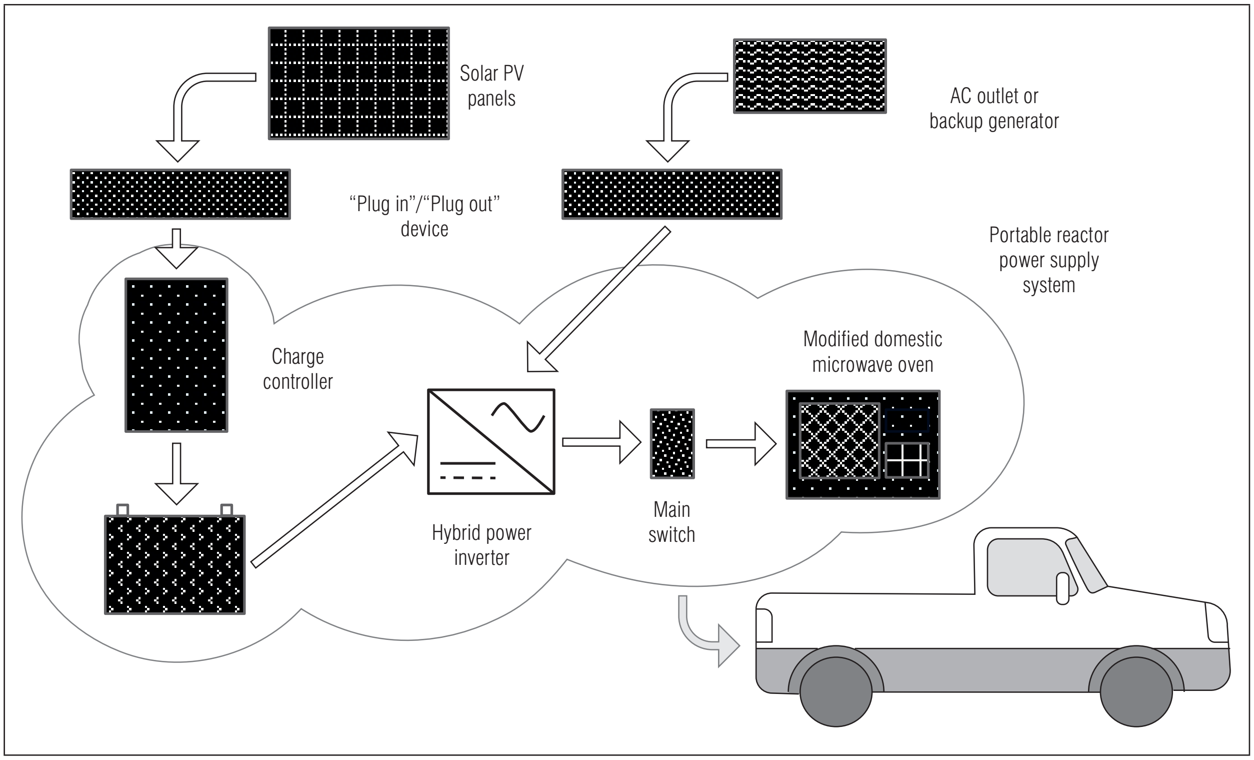

Figure 2. System connection diagram of the modified microwave pyrolysis unit.

value of the proposed system is the possibility of easy transport, thanks to the fact that the components of the portable subsystem do not require much space under the power and time conditions previously mentioned.

In addition, for this to be viable, easy connection/disconnection devices must be available, guaranteeing the location of the power source. Thus, for the established power and duration characteristics, a 2-kW inverter is required, and the storage system can be achieved with only a 100 Ah battery, depending on the desired autonomy. In contrast, a storage system such as the one obtained is relatively small, which allows us to understand the costs of biochar production at fixed stations assisted by microwaves that range around 0.52 USD/kg (Zhu *et al*., 2022) (Neha *et al*., 2022). This shows that technology exists to facilitate the reduction of organic waste from agricultural activities in a sustainable way, avoiding collection in large quantities and with the possibility of adjusting it to the needs of each region.

CONCLUSION

Solid waste is a growing problem, and the organic fraction represents more than 50%, so the application of circular economy in its use is a great opportunity. It can be used in organic amendments production, such as compost, biochar, and hydrochar, using as a raw material: fruits, vegetables, plant crops, and even animal residues. However, depending on the source, the product can differ substantially, and it is important to generate control mechanisms to verify the quality of the final products. As was shown in the compost physicochemical analysis, the presence of heavy metals in some sources was observed. Biochar and hydrochar showed more homogeneous results in physicochemical terms; however, they are devoid of microorganisms, so their mixture with compost is not ruled out. As an added value, the design of a sustainable and portable reactor to produce biochar and hydrochar in local communities, which uses microwaves for pyrolysis, is an easy way and opportunity for the field, because it helps in the reuse of solid waste and the generation of organic material with some nutrients for plants.

Conflict of interests: There were no conflicts of interest among the authors of this academic research. We declare that we have no financial or personal relationships that could influence the interpretation and publication of the results obtained. We always guarantee compliance with ethical standards and scientific integrity, in accordance with the guidelines established by the academic community and those dictated by this journal.

Author's contributions: RGF: biochar and hydrochar production and physicochemical analysis. JMGD: analysis of organic waste, generation and use in Colombia. Case studies. OFCR: Compost production. AFPH: Proposal for a sustainable and portable reactor to produce biochar and hydrochar for local communities using small-scale agro waste.

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