Review [Revisión]

A GLOBAL VISION OF AGROECOLOGICAL PRACTICES FOR RECYCLING AGRICULTURAL WASTE: LIMITATIONS AND POTENTIALS IN TERRITORIAL CONTEXTS †

[UNA VISIÓN GLOBAL DE LAS PRÁCTICAS AGROECOLÓGICAS PARA EL RECICLAJE DE RESIDUOS AGRÍCOLAS: LIMITACIONES Y POTENCIALIDADES EN CONTEXTOS TERRITORIALES]

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SUMMARY

Background. Agroecological practices (AP) for managing agricultural waste (AW) available in agroecosystems represent an opportunity to mitigate the negative effects caused by conventional agricultural practices. However, knowledge gaps persist regarding the options for their management and the territorial context of application. **Objective.** To identify APs with potential for AW management. **Methodology.** The first phase, a bibliometric analysis was realized with a query in the Web of Science (WoS) search engine with the phrase "Agroecological practices for the management of agricultural waste". The search database was analyzed with the VOSviewer software to delimit thematic groups and identify AP for managing AW. The second phase involved a technological surveillance (TS), which consisted of the description, analysis, and selection of the territorial environment where its development is possible, with the aim of identifying the AP with the highest potential for recycling AW into agroecosystems. **Results**. It was found that 71% of the scientific publications are from the last four years. Six keyword clusters were identified, which based on node size and proximity to each other are located: 1) management, 2) nitrogen, 3) manure, 4) carbon, 5) compost and 6) soil. **Implications.** The analysis allowed to identify the techniques of anaerobic digestion (AD), composting and biochar with potential for the reintegration of AR. **Conclusion.** The reintegration of AW presents an opportunity to promote the sustainability of agroecosystems through agroecological principles such as nutrient recycling into the soil and energy recovery. This study highlights that the recycling of AW is essential for initiating an agroecological transition, with composting being a key technology for direct implementation and improving the sustainability of food systems.
Key words: Agroecological practices; agricultural waste; recycling; territorial contexts.

RESUMEN

Antecedentes. Las prácticas agroecológicas (PA) para el manejo de residuos agrícolas (RA) disponibles en los agroecosistemas representan una oportunidad para mitigar los efectos negativos causados por las prácticas agrícolas convencionales. Sin embargo, persisten vacíos de conocimiento sobre cuáles son las opciones para su manejo y el contexto territorial de su aplicación. **Objetivo.** Identificar las PA con potencial para el manejo de RA. **Metodología.** La primera fase, se realizó un análisis bibliométrico con una consulta en el buscador *Web of Science* (WoS) con la frase "Agroecological practices for the management of agricultural waste", la base de datos de la búsqueda se analizó con el software VOSviewer para delimitar grupos temáticos e identificar las PA para el manejo de RA. La segunda fase fue una vigilancia tecnológica (VT), que consistió en la descripción, análisis y selección de su entorno territorial, en el que es posible su desarrollo con el propósito de reconocer la PA con mayor potencial para reciclar los RA a los agroecosistemas. **Resultados.** Se encontró que 71% de las publicaciones científicas son de los últimos cuatro años. Se

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identificaron seis conglomeraciones de palabras clave, que en función del tamaño del nodo y cercanía entre ellos se ubican: 1) gestión, 2) nitrógeno, 3) estiércol, 4) carbón, 5) composta y 6) suelo. **Implicaciones**. El análisis permitió identificar las técnicas de digestión anaerobia (DA), compostaje y biochar con potencial para la reintegración de RA. **Conclusión.** La reintegración de RA ofrece una oportunidad para promover la sostenibilidad de los agroecosistemas a través de principios agroecológicos como el reciclaje de nutrientes al suelo y el recuperamiento de energía. Este estudio destaca que el reciclaje de RA es fundamental para iniciar una transición agroecológica, siendo el compostaje una tecnología clave de implementación directa y mejorar la sostenibilidad de los sistemas alimentarios.
Palabras clave: Prácticas agroecológicas; residuos agrícolas; reciclaje; contextos territoriales.

INTRODUCTION

Abundant amounts of agricultural waste (AW) are continuously generated in various intensive agricultural systems (Duque-Acevedo *et al*., 2020), as producers opt for innovations based on increasing the yield of their crops and ignore the potential use of reintegration of waste generated on their own farms, as it is not considered a resource of significant monetary value (Kumar *et al*., 2024). According to Liu *et al*., (2024), 1.3 billion tons of AW are generated annually, so these wastes create environmental and health problems, emerging as a possible solution for their reintegration into agroecosystems through the application of agroecological practices (AP) (Agapkin *et al*., 2022).

APs improve food systems by creating beneficial biological interactions and synergies between elements of agroecosystems, to increase input efficiency, resource availability and minimize the use of external inputs (Wezel *et al*., 2020); prioritizing ecosystem processes and services, integrating them as fundamental elements in the development of APs (Wezel *et al*., 2014).

In this sense, the development of practices that involve agroecological principles such as: nutrient recycling, input reduction and soil health, must be increasingly used as strategies to mitigate the negative effects caused by conventional agricultural practices (Çakmakçı *et al*., 2023) and in relation to AW, focused on the management of resources available in agroecosystems to transition towards sustainable food systems (Wezel *et al*., 2020).Currently, APs that reintegrate waste generated on and off farms represent a solution to minimize food losses and waste (FLW), focusing on losses at the primary production stage (O'Connor *et al*., 2022, FAO, 2018).

Within the context of value chains, agricultural losses remain a primary concern in low-income countries (Fabi *et al*., 2021). The Food and Agriculture Organization of the United Nations (FAO) in 2019 estimated that losses during primary production amounted to 14% globally. Therefore, the generation of AW will continue to occuring as population demands increase (Sonu *et al*., 2023).

In recent years, there has been a growing interest in AP research with the objetive of obtaining better methods for the revaluation of AW that contribute to mitigating climate change (Blasi *et al*., 2023, Shinde *et al*., 2022, Jeswani *et al*., 2021; Chew *et al*., 2019), improving soil fertility (Arias *et al*., 2023, Awasthi *et al*., 2020; Robles *et al*., 2020), nutrient availability (Nanda and Berruti, 2021) and soil carbon sequestration potential (Galindo-Segura *et al*., 2020). However, knowledge gaps persist that would be advisable to investigate regarding the options for their management and territorial context of application.

Furthermore, there are review articles that address the potential use of AP for sustainable agriculture (Wezel *et al*., 2014), and detailed reviews of each AP for the management of AW (Kumar *et al*., 2021; Kunatsa and Xia, 2022 and De Corato, 2020), but there is a limited research that addresses a comprehensive review of existing AP with potential for the management of AW to incorporate into the soil.

Therefore, the objective of this work is: a) to identify AP with AW management potential through a bibliometric analysis and b) to analyze their potential, limitations and application in territorial contexts through technological surveillance (TS). This analysis of the territorial context seeks to select the most viable AP to be established as part of a regional strategy with producers using AW as an element reintegrated into agroecosystems and strategy capable of enduring fort the foreseeable future.

MATERIALS AND METHODS

This research was carried out in two phases (Figure 1): bibliometric analysis and the TS. In the first, a query was made in the Web of Science (WoS) database using the phrase "Agroecological practices for the management of agricultural waste" was used as a search criterion in titles, abstracts or keywords in documents in English, obtaining a list of 680. As a search filter, it was restricted to documents published from 2014 to March 2024 and research that did not evaluate AP for the reintegration of AW into the soil was excluded, discarding those such as "crop diversification" (Madsen *et al*., 2021), "water conservation" (Hawes *et al*., 2021) and "tillage reduction" (Palomo-Campesino *et al*., 2022). Which yielded a total of 488 documents which were used for the analysis. Smart tools were used to track, analyze and visualize WoS research, thus determining the annual production of published studies on the subject, the area of knowledge of scientific journals, leading authors in research and affiliated institutions. These data were recorded in an Excel® database (V.18.0).

The selected articles were exported to the VOSviewer 1.6.14 software (Van Eck and Waltman, 2010), to establish the elements and connections of an analysis network, allowing the creation of co-occurrence network maps, together with keyword connectivity networks, where the elements with higher similarities are placed closer to each other and enabling the visual identification of the main thematic axes of the research and highlighting the missing areas of knowledge on the topic. The bibliometric analysis allowed the identification of trends and research areas, as well as the reinterpretation of the accumulated scientific knowledge on the most relevant PAs for the management of AWs, providing coherence to large data sets easily accessible in scientific databases (Nikiema *et al*., 2023; Arias *et al*., 2023).

The TS was conducted with the aim of thoroughly identifying agroecological practices, in order to establish the most promising alternative for reintegrating AW into agroecosystems. According to Arango-Alzate *et al*. (2012), once the alternatives for AW management are identified, the next step was to characterize the requirements for the development of practices, analyze the information, and select the territorial environment for implementation. This stage was subdivided into two phases: the first phase consisted of describing and analyzing each of the technologies identified as APs for AW management from the WoS bibliometric analysis (advantages and disadvantages). The second phase focused on identifying the territorial environment, meaning specifying the characteristics of the area to implement each AP with the highest potential to recycle AW *in situ* into high-value-added products for soil amendment.

RESULTS AND DISCUSSION

Bibliometric analysis

Annual production of studies

In 2021, a decrease in the number of articles was recorded. In the last two years, an increase in the number of AP studies for the management of AW was observed (Figure 2). From 2020 to date, 71% of the total publications have been published. By 2024 and up to the date of consultation, a similar number has been published as in 2014 and 2015.

Knowledge area of scientific journals

According to the classification conducted by WoS, the main research sources (scientific journals) where research on the utilization of AW in AP have been published are: Environmental Sciences, Environmental Engineering, Green Sustainable Science Technology and Environmental Studies (Figure 3). 40.79% of the documents found were published in Environmental Sciences, of which 80% correspond to studies on the potential AW used as nutrient recycling and carbon sequestration in the soil, thus reducing the use of chemical inputs and causing positive environmental impacts (Pergola *et al*., 2018).

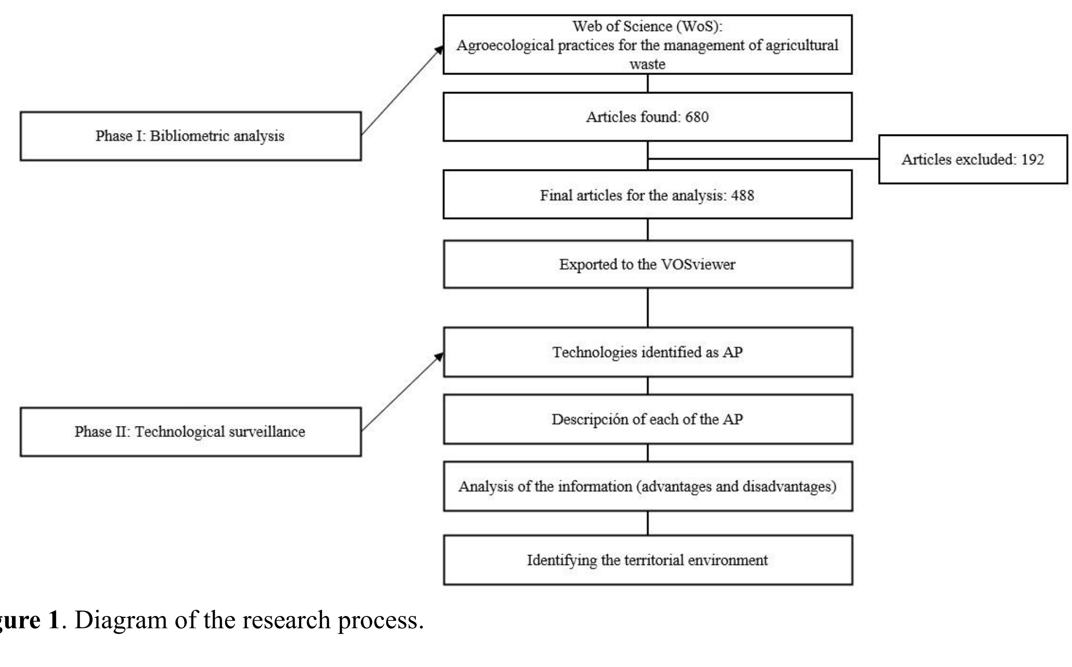

Figure 1. Diagram of the research process.

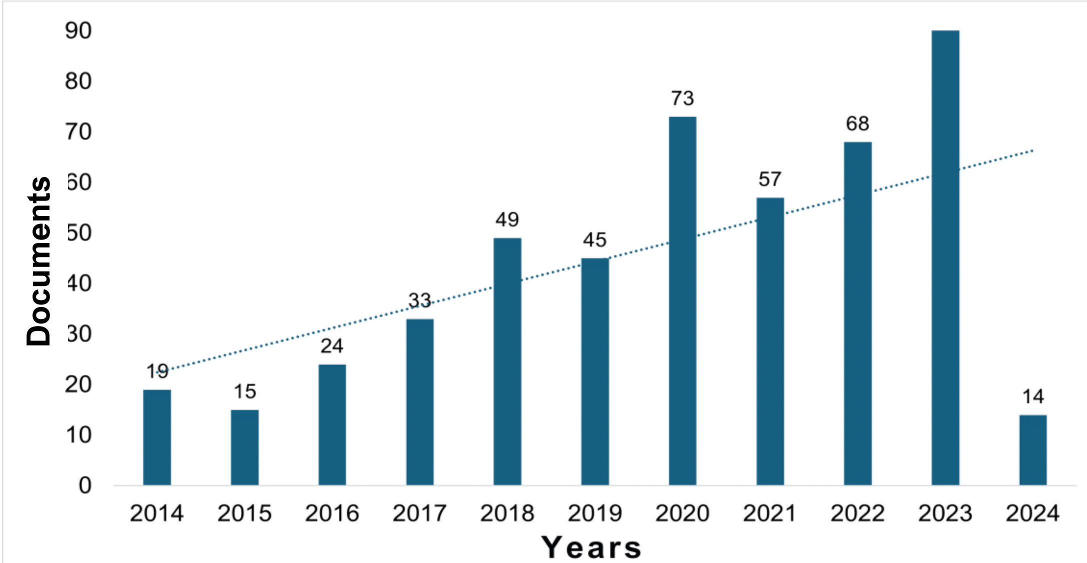

Figure 2. Production of documents related to agroecological practices that recycle agricultural waste. Source: own elaboration based on WoS.

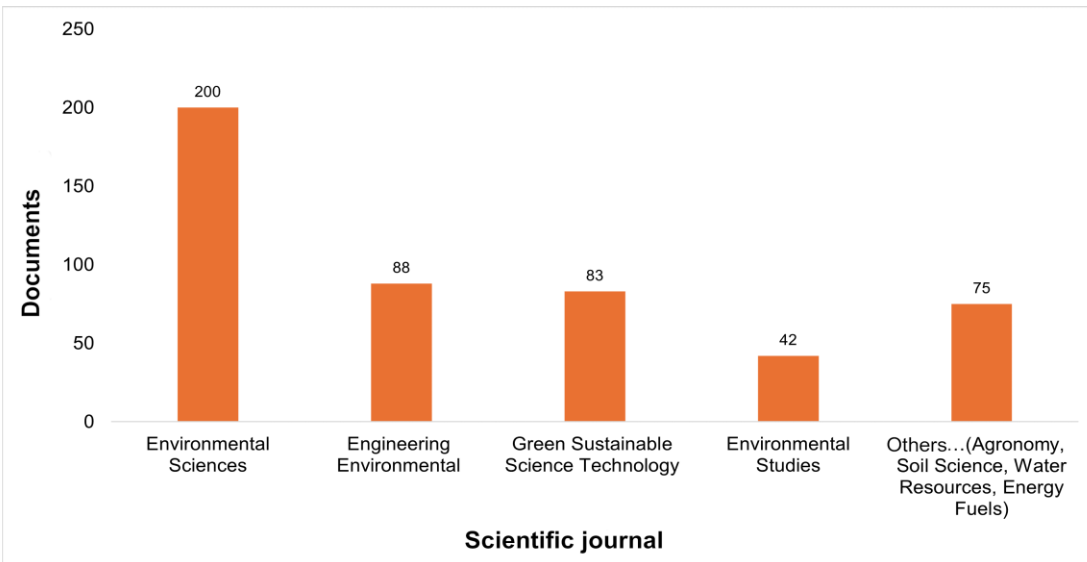

Figure 3. Scientific journals with the highest production of publications in the area. Source: own elaboration based on WoS.

Leading Authors in Research

The authors with the highest number of citations were Francesco Montemurro and Mariangela Diacono from the Metaponto Research Institute and the University of Bari in Italy, with a total of 179 and 161 citations, respectively, as well as 103 studies each, making them prominent figures in the literature on waste and agricultural by-product management in biofertilizer production. Other notable researchers, based on their citation levels, include Gwenzi Wills from the University of Kassel in Germany, with five documents and 157 citations focused on the development of nitrogen fertilizers to enhance corn yield; Oenema Oene from China Agricultural University, with four documents and 77 citations, recognized for his research on nutrient recycling from manure generated by urban livestock operations; and Simha Prithvi from the Swedish University of Agricultural Sciences, with four documents and 58 citations, who is distinguished for studies on nutrient recycling from crops and manure, conducted at the laboratory level with a circular bioeconomy approach. In Mexico, authors addressing the revaluation of AW also approach this issue from a transition towards a circular economy perspective (Cunha Zied *et al*., 2020; Ozcariz-Fermoselle *et al*., 2019).

Co-occurrence Analysis of Keywords

In the cluster analysis of keywords related to AP that manage AW (Figure 4), the relevance of the words in the network is represented: the larger the circle and the closer the proximity between two circles, the greater the co-occurrence or citation of the keyword within the dataset being analyzed (Galindo *et al*., 2020). The co-occurrence analysis of keywords extracted from the 488 articles in the WoS database showed the connection between research on AP for AW management and other globally relevant trends, as well as the recognition of technologies for their treatment.

Six clusters of keywords were identified, which are located based on the size of the node and proximity between them: 1) management, 2) nitrogen, 3) manure, 4) carbon, 5) compost and 6) soil. The first cluster of words on management (red color) is related to waste, recycling, circular economy, waste management, agriculture, life cycle assessment, nutrient recovery and energy.

In the nitrogen word cluster (green color), the most relevant terms were sustainability, systems, and anaerobic digestion (AD). The latter, although it could not be appreciated, was identified as the first AP for AW management; classified as a technology that can manage organic substrates in biogas (Karki *et al*., 2021 and Rasapoor *et al*., 2020). In relation to the most segregated words were conversion, bioenergy, and sustainable agriculture. This could be related to the lack of studies that improve biomass conversion through AD that can be used for sustainable bioenergy production and to obtain high biogas yields (Zheng *et al*., 2014).

The most relevant words for manure (navy blue) were yield, biogas and emissions, reiterating that the addition of manure is the main source of biogas production by AD (Qin *et al*., 2022), producing clean energy and low carbon emissions (Jin *et al*., 2021). On the other hand, the most distant words were ammonia, digestate and field, this may refer to the fact that ammonia is an essential nutrient for bacterial growth and can inhibit metagenesis during the AD process, especially when dealing with substrates such as manure or the organic fraction, so the scientific literature indicates that the recovery of AD systems after ammonia inhibition is possible, but that it has been scarcely studied (Yenigun and Demirel, 2013). Regarding the words digestate and its application to the field as organic amendments, research points to the agronomic properties of digestates and their effects on the soil as a positive organic amendment that have been little explored (Nkoa, 2014).

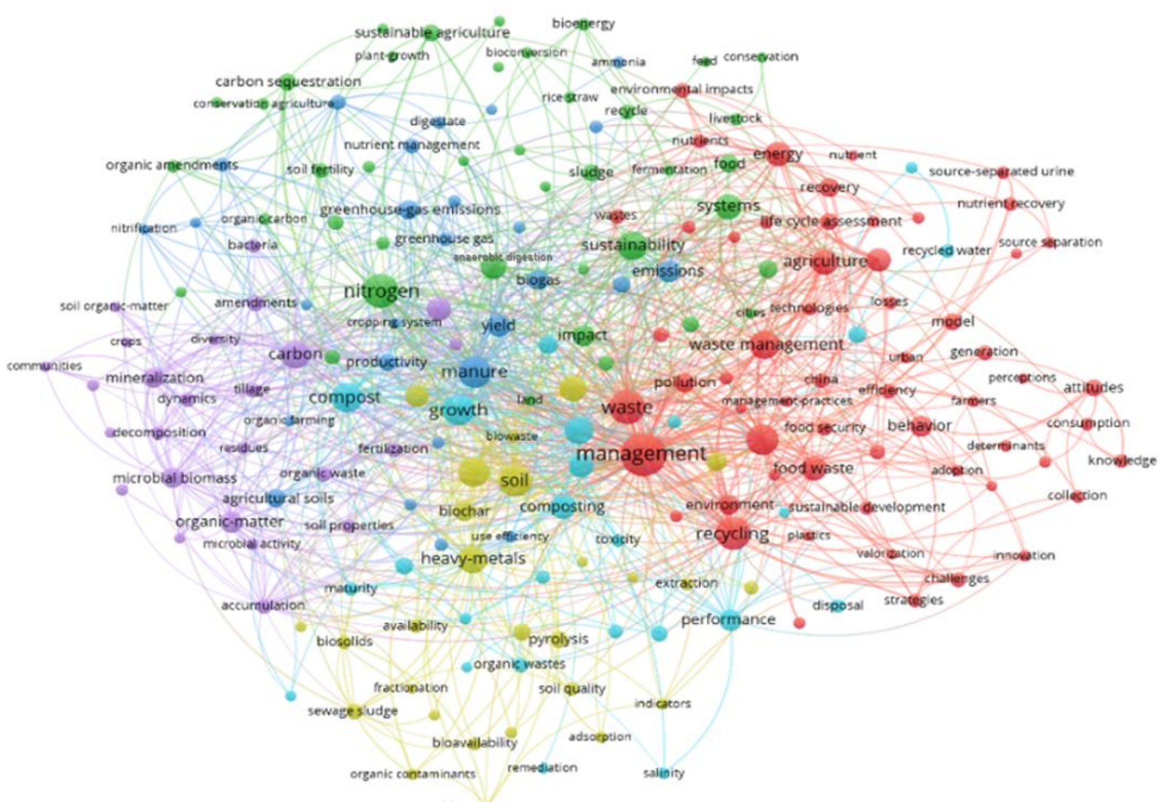

Figure 4. Co-occurrence Network of Agroecological Practices for Agricultural Waste Management.

For the carbon area (purple color), the terms amendments, fertilization and organic matter were distinguished, meaning that the application of AW as amendments or organic fertilizers would allow replacing chemical fertilizers and theoretically allowing the recovery of carbon (C) and nitrogen (N) contained in AW, which are usually eliminated in the process in a passive way promoting the emission of greenhouse gases (GHG) (Sharma *et al*., 2019). Regarding the most segregated words, microbial communities and biomass were found as areas of study to improve the effectiveness, as well as the times of the degradation of organic matter (Suleiman *et al*., 2018).

For the compost cluster (light blue), the terms growth, quality, urban solid waste (USW) (although they cannot be seen within the network) and composting were identified. This last word was the one that showed the greatest co-occurrence with respect to AW management and the greatest affinity for recycling, supporting that the composting process is one of the most used technologies to reduce food losses and nutrient recovery through recycling (Sayara *et al*., 2020; Walling and Vaneeckhaute, 2020).

The words segregated in this network about composting were organic waste and remediation, which indicates an important area of opportunity for research on the positive effect of this AP due to the fact that there is a diversity of waste that have not been applied to this technology (Palaniveloo *et al*., 2020; Ayilara *et al*., 2020), as well as the final product of this AP, compost, can be applied for the bioremediation of a wide variety of contaminants found in the soil such as hydrocarbons and heavy metals, thus enriching soils contaminated by anthropogenic activities (Sayara *et al*., 2020).

In the soil word cluster (yellow), there is a closer relationship with the terms heavy metals, pyrolysis and biochar; this term identified as the third AP with potential to stabilize carbon in residual biomass, through pyrolysis and its capacity to remediate soils contaminated by heavy metals (Song *et al*., 2016) and, finally, the words segregated from this section were risk assessment, organic contaminants and biological availability, referring to the possible limitations of this practice with respect to its capacity to selectively adsorb contaminants, as well as the availability of the AW that is being considered in the process (Kavitha *et al*., 2018). The bibliometric analysis identified three AP (AD, composting and biochar) for the management of AW, as well as the areas with the greatest current research potential, as well as those with a lower number of investigations in the last 10 years.

Technological Surveillance

After the identification of the APs carried out in the bibliometric analysis, those that address the topic of recycling of AW were analyzed. 30.73% of the consulted documents indicated that AD is one of the most widely used techniques for the use of agricultural waste (Karki *et al*., 2021; Zamri *et al*., 2021 and Wainaina *et al*., 2020). 25.20% of the documents address the topic of composting (Awasthi *et al*., 2020, Robles *et al*., 2020 and Palaniveloo *et al*., 2020) and 23.77% focus on the potential of biochar for use on farms from AW (Seow *et al*., 2022 and Jeyasubramanian *et al*., 2021).

Anaerobic Digestion

AD is a solid waste upgrading route with a sustainable approach to bioenergy recovery (Zamri *et al*., 2021). During the AD process, various microbial communities intervene (hydrolysis, acidogenesis and metagenesis) which transform the organic carbon present in the waste, converting it into its most reduced and oxidized forms, producing methane gas (CH_4) and carbon dioxide (CO_2) respectively, carrying out all stages in the absence of oxygen (Madsen *et al*., 2011). The AD process uses various substrates that can be classified into three categories: AW, industrial and domestic (Wainaina *et al*., 2020). Sometimes, sludge from wastewater treatment is also used (Kumar *et al*., 2021). Currently, the positioning of this technology in the market is done in order to handle food generated from industrial and domestic activities (Jin *et al*., 2021).

Similarly, waste from the harvest such as wheat straw, corn stover, sugarcane bagasse and forestry waste are used, however, one of the most common challenges associated with food waste in the AD process is the high moisture content and acidic pH (Agrawal *et al*., 2023). Therefore, various investigations recommend the implementation of animal manure to increase the pH, as well as the dry matter content to obtain higher methane yields (Fernandes *et al*., 2023 and Lemes *et al*., 2023). This AP has great potential for application in crop agroecosystems that generate a large amount of stover at the farm and family farm level where agricultural activities are also carried out to take advantage of animal excrement to enhance the production of biogas generated for households in rural areas (Locoli *et al*., 2019).

Composting

Composting is a controlled process under aerobic conditions to degrade organic matter through the action of microorganisms to produce organic fertilizer called compost (Ayilara *et al*., 2020). This waste degradation technique has been a fundamental process in agriculture due to the recycling of agricultural waste (biomass), through the composting process that guarantees the production of a fertilizer with a high content of minerals and beneficial microbial consortia associated with the soil and crop plants to increase their nutritional status, health and productivity (Waqas *et al*., 2023).

In recent years, composting has emerged as an eco-friendly, cost-effective and safe treatment technology to manage mainly agricultural residues from crop residues, plant residues and food waste generated substantially and imperatively globally (Wang *et al*., 2019). Furthermore, the growing need for a bioeconomy has boosted techniques such as composting of agricultural biomass residues as a viable option with multiple benefits such as improved soil quality through carbon and nutrient-rich fertilizers (Nanda and Berruti, 2021), reduction of agricultural residues on farms (De Corato *et al*., 2020), reduction of synthetic fertilizer application (Khoshnevisan *et al*., 2021), increased crop productivity (Awasthi *et al*., 2020) and derivation of by-products such as leachate-based tea and compost (Siddiqui e*t al*., 2011).

Although there is a large amount of research related to the improvement of the composting process, the innovation of this technology focuses on the application of microbial consortia (protists, fungi, oomycetes, yeasts, actinomycetes and bacteria) that act as biological control agents to improve the quality of the compost and improve process times (De Corato *et al*., 2020). Without leaving aside, that composting also offers another alternative for the management of AW, which is vermicomposting, differentiated by its application of earthworms (Maharjan *et al*., 2022).

However, composting also has some potential shortcomings such as long processing time, N loss and sometimes immature composts for land application (Chen *et al*., 2023). However, despite its disadvantages, this technique is widely recognized and more common to find at farm level (De Corato *et al*., 2020). In addition to its main application being as a fertilizer, composting also offers erosion mitigation (Pottipati *et al*., 2023), improved stormwater infiltration (Maturi and Kalamdhad, 2023), contributed to the carbon sequestration process (Panettieri *et al*., 2022), and restoration of contaminated sites (Mazumder *et al*. 2023).

According to Maturi and Kalamdhad, (2023) they carried out a scientific mapping of the countries that revalue their agricultural waste through the composting process, placing Spain, China, India, Brazil, Italy and the United States as the countries with the most active participation in the field of this technique and positioning Mexico in 12th place in contributions in the study of the application of composting on a pilot scale and with potential for its application in strategies to manage waste flows in various regions. The potential highlighted by this AP is that it can be applied in both rural and urban areas, taking advantage of the generated AW to enrich soils in various sectors, specifically in agricultural contexts, thus improving eroded soils and enriching soils in large areas of land and open-air in rural areas (Niles, 2020).

Biochar

Biochar is a process in which solid material is transformed through the thermochemical conversion (pyrolysis) of biomass at more than 250 ºC in the total or partial absence of oxygen, producing a low-density, carbon-rich porous material that is produced for the purpose of generating soil fertilizer and carbon sequestration (Galindo-Segura *et al*., 2021; Chen *et al*., 2019). Due to the demands of food security, environmental protection and reduction of greenhouse gas emissions, biochar has gradually been linked to soil management and sustainable agricultural development because it can improve the physicochemical characteristics of the soil with greater retention of moisture, nutrients, greater aeration and root penetration, becoming a potential reservoir of nutrients (Hossain *et al*., 2020; Chew *et al*., 2019).

One of the advantages of this technology is that it has a higher conversion rate than other nutrients, such as plant biomass, followed by wood and manure. However, some research reports that if the objective of the research is to increase carbon content, it is primarily recommended to use plant-based AW (Arias *et al*., 2023). The biochar technique has positioned itself in the organic fertilizer market as a promising technology focused on soil improvement, as its application increases crop yields, as well as nutrient and water use efficiency, and the potential for sequestering bioavailable metals and antibiotics in contaminated soils (Senadheera *et al*., 2023). Current scientific literature focuses on in-depth studies of the effects of the biochar production process on its properties (Danesh *et al*., 2023).

Although the biochar process can have economic advantages by reducing the acquisition of fertilizers and increasing the added value to crops, but also the process of obtaining it can be more complex than composting and vermicomposting techniques (Dickinson *et al*., 2015). According to Campion *et al*., (2024), mentions that the profitability and desirability of biochar production are very uncertain and adapted to the particular circumstances of each situation, which vary according to aspects such as geographic location, resources used, project size, thermal processing conditions, agriculture practiced and consideration of external effects, which presents challenges for private investors.

Territorial Context of AP Development

Figure 5 highlights the territorial contexts in which the APs described in the TS are developed. It is interesting to note that most of the documents reviewed refer to the classification of AWs in which each technology is applicable and there is little research that recommends the environment in which each of the APs are developed.

Through the TS, some documents were identified that recommend the territories with the potential to develop each AP. For example, most research recommends that AD technology be located near livestock farms due to the use of AW, specifically manure (Agrawal *et al*., 2023 and Fernandes *et al*., 2023), to optimize biogas production (Silwadi *et al*., 2023). Other authors also point out that the establishment of AD plants is viable in areas where MSW discharges are deposited, usually in regions surrounding cities or underdeveloped areas (Zamri *et al*., 2021; Lee *et al*., 2021).

In the case of composting, this is the most common AP to be found at the farm level and near crop systems (De Corato, 2020) and recommended in those regions where agricultural production is vital to ensure the livelihoods and promote the economic growth of producers (Panda *et al*., 2022). In addition, this technology offers an opportunity to be developed at different levels such as at the agro-industrial, domestic and agricultural levels (Waqas *et al*., 2023). Finally, some documents recommend the implementation of the biochar practice in warm and tropical climatic regions (Senadheera *et al*., 2023), for the use of waste generated in tropical crops in order to obtain an optimal temperature during the pyrolysis process to have a more suitable product as a soil amendment (Chin-Pampillo *et al*., 2021).

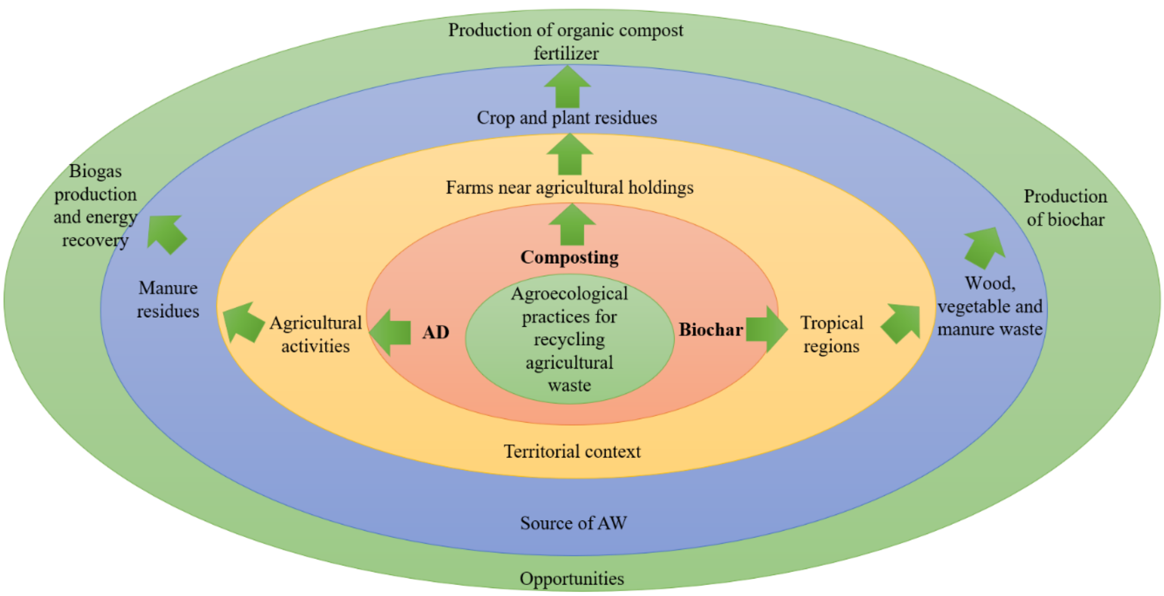

Figure 5. Territorial context of AP in the management of AW.

CONCLUSIONS

The recycling of AW through agroecological technologies and practices represents an opportunity to promote the sustainability of agroecosystems, as well as energy recovery in agriculture. Anaerobic digestion techniques, such as composting and biochar, are the most common for AW management. This work provides information based on a bibliometric analysis and technological surveillance, identifying that the area of opportunity in AW management focuses on knowledge, innovation, perceptions, challenges, and strategies. These terms are related to the involvement of stakeholders who integrate their knowledge (farmers and scientists) to address complex issues in agroecosystems innovatively for AW management. This is particularly relevant as the recycling of their waste by farmers is considered a crucial cornerstone for initiating an agroecological transition on their farms. Finally, the technological surveillance helped to determine that the potential of AP is in energy and biogas generation (anaerobic digestion) and organic fertilizers (biochar and compost), establishing composting as a AP that implements direct recycling of RA in the form of compost, thereby recycling nutrients back into the agroecosystem.

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Compliance with ethical standards. Not applicable due to the nature of the study.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request (felipegl@colpos.mx).

Author contribution statement (CRediT). L.A. Morales-Mendoza – Conceptualization, Methodology, Writing – Original draft – review and editing. **F. Gallardo-Lopez** – Conceptualization, Formal Analysis & editing; **M.A. Hernández-Chontal** – Investigation, writing-review & editing. **R.I. Castillo-Zamudio** – Data curation, Review & editing.

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