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Botanical pesticides as a sustainable pest control strategy: Case of polyphenolic extracts of coffee pulp (*Coffea arabica*)

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ABSTRACT

Agriculture remains one of the main economic activities in many countries; however, due to this and the use of a conventional model, the application of chemical pesticides has become more frequent. Botanical pesticides are a sustainable alternative for integrated pest management (IPM), where polyphenolic extracts can play an essential role due to their natural abundance and extraction methods. A variety of studies on botanical pesticides in relation to sustainability have been reported in recent years; however, coffee pulp (*Coffea arabica*) remains an under-documented resource in the context of agricultural applications. This review aims to analyze the limited research available on the extraction of polyphenols from coffee pulp and their application as insecticidal, fungicidal, and antibacterial agents. The purpose is to demonstrate the potential of coffee pulp as a sustainable botanical pesticide and its relevance as an environmentally friendly alternative for IPM. By synthesizing existing findings reviewed literature, the study identifies current knowledge gaps in the application of coffee pulp polyphenols for pest control and highlights the compounds responsible for these effects. Regarding the effects of polyphenols on the environment and human health, it shows that based on available information, they cannot be regarded as a risk and may therefore continue to be a sustainable alternative in IPM. Simultaneously, it was discovered that the insecticidal and fungicidal activity of this botanical pesticide have been more extensively studied than antibacterial properties. This review underscores the potential of coffee pulp as a sustainable and environmentally friendly botanical pesticide and emphasizes the need for further research in underexplored areas, particularly antibacterial applications.

Keywords: antibacterial, antifungal, insecticide, polyphenols, pulp, sustainability.

INTRODUCTION

In nations deemed less developed, agriculture can account for over 25% of the gross domestic product (GDP), making it a crucial activity to fight extreme poverty, increase wealth, and provide food for future generations, according to the World Bank (The World Bank Group, 2024). Conversely, it is projected that over 1.8 billion people worldwide work in agriculture, primarily using conventional production techniques, intending to satisfy the rising demand for food due to population growth and the necessity for society to have more money accessible (Moracanin et al., 2021). The term "sustainability" applied to agriculture describes how the food needs of the growing population are met by ensuring a minimum impact on the environment and people's health, as well as the profitability of the products (UCDavis, 2021). There is an agreement that agricultural sustainability must address social, economic, and environmental challenges, but estimating sustainability in an agricultural system is still difficult and imprecise (Lykogianni et al., 2021).

Agriculture faces significant problems that jeopardize sustainability because conventional production methods are prevalent. These challenges include managing natural resources efficiently, increasing productivity, and combating diseases and pests (Guzman-Alvarez et al., 2022). Chemical compounds or mixtures of these so-called pesticides, which are defined by preventing, destroying, or controlling organisms considered pests, such as insects, fungi, rodents, or undesired plant species that cause damage during the production and storage of crops, have been used to address the issues associated with this last category (Abubakar et al., 2020).

Pesticides have been widely used on crops for pest control, mainly in the early "industrial era" from the 1950s onwards (Hassaan and El Nemr, 2020). While the use of chemical compounds in agriculture is controlled for a limited number of compounds, agriculture is one of the few sectors in which chemicals are intentionally dumped into the environment (Warra and Prasad, 2020).

However, while pesticides have significant advantages in controlling pests, including diseases and weeds, and eliminating vectors, health problems caused by direct exposure, handling, or pesticide residues in food products have also been reported (Palaniyappan et al., 2022). Additionally, misuse of these products in pest control could cause environmental alterations of the soil and water, and be harmful to other creatures such as birds, fish, insects, and non-target vegetation (Rani et al., 2021).

The goal of Integrated Pest Management, or IPM, is to provide high-quality, ideal yields without endangering human health or the environment. Its foundation is the sustainable use of pesticides, with a primary focus on the employment of non-chemical protection techniques (Jamiołkowska and Kopacki, 2020). Because of this, plants that contain bioactive compounds have been utilized as substitutes for extracts in the control of various bacteria, viruses, fungi, and pests, making them botanical pesticides (Ndolo et al., 2019).

Within these compounds are metabolites such as terpenes, alkaloids, and polyphenols (Hassan et al., 2021). The use of this last chemical family as a sustainable alternative has spread due to its distribution, natural abundance, various chemical structures, and sources of obtaining within Yan et al., 2021), which plant parts such as roots, leaves, stems, fruits, and residues can be mentioned (Hoesain et al., 2021). This has led to its study for decades in food-related applications (Khan et al., 2024) and the isolation of active compounds (Chacón-Vargas et al., 2024). More recently, it has been explored for use as a botanical pesticide.

However, there are abundant residues from agricultural-producing countries that have not yet been studied or have been only minimally evaluated. Coffee pulp is among these. Figure 1 presents a proportional schematic summary of reviews focused on polyphenols, botanical pesticides, and their intersection in the context of coffee pulp (highlighted by the red dot in the image), illustrating that coffee pulp has been scarcely studied for its application as a botanical pesticide and its potential role in sustainability.

The study of coffee pulp is of great importance due to the high consumption of coffee in European countries such as France, Spain, and

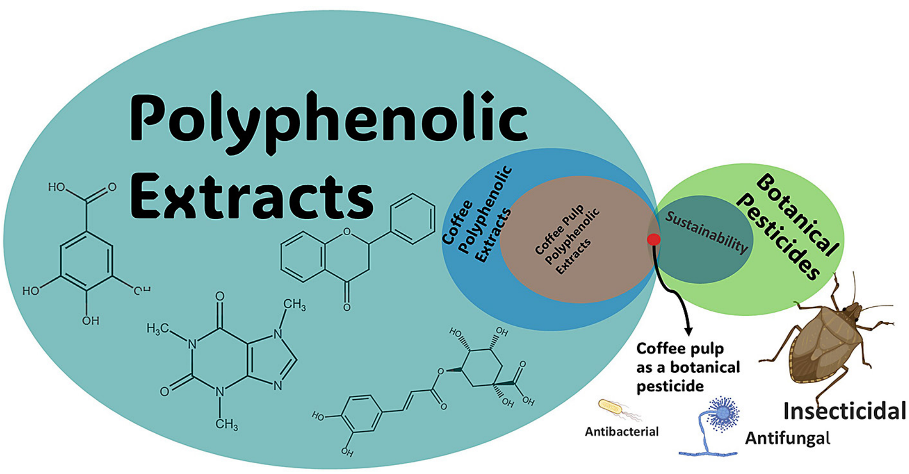

Figure 1. Relationship between studies on polyphenols, coffee pulp polyphenols, and their intersection in the context of application as botanical pesticides

Italy, as well as in American countries like Canada (Bookman, 2013; Samoggia and Busi, 2023; Torres-Collado et al., 2018). Additionally, it is highly relevant for coffee-producing countries such as Colombia, Mexico, Brazil, Thailand, and India, which face the challenge of managing coffee waste in a more sustainable manner (Ashardiono and Trihartono, 2024; Chaovanapoonphol et al., 2023; Hernández-Loarry and Barradas, 2024; Prakash et al., 2015; Samoggia and Fantini, 2023).

According to the International Coffee Organization (ICO), the sector continues to grow in production and consumption due to the average annual growth rate since 1990 being 2.5%, and total production increased from 93.5 million 60 kg bags to 168.2 million bags in 2022 (International Coffee Organization, 2024b). Likewise, this agency reported a total of 7.075 million 60 kg bags of arabica coffee in exports from the registered countries until June 2024, making it the most exported variety (International Coffee Organization, 2024a).

In terms of process, coffee production has a sequence of separating the elements of the fruit other than the coffee seed, which are considered processing residues. Among these residues are peel, coffee pulp, mucilage, husks, silver skin, and others (Blin et al., 2017). It is estimated that for every 1 metric ton of coffee fruit produced, 0.615 metric tons of waste are generated, of which 93% is not utilized. This quantity of loss varies depending on whether the processing method is wet or dry (Rojas-Sossa, 2015).

The pulp of coffee is mainly composed of carbohydrates, minerals, and proteins, in addition to containing high levels of caffeine, chlorogenic acid, tannins, and phenolic compounds (Le et al., 2023), due to this composition, it has been used as a biofertilizer, animal feed concentrate, and nutritional product for human consumption, as well as other bioproducts and bioenergy, in addition to bioactive compounds such as phenols (Carmen et al., 2020) make pulp an excellent raw material to obtain products with antioxidant and antimicrobial capacity (Rossetto et al., 2020).

A variety of studies on botanical pesticides in relation to sustainability have been reported (Khodijah et al., 2024; Mahawer et al., 2025); however, coffee pulp remains an under-documented resource in the field of agricultural application as a botanical pesticide. This study aims to present the findings from the limited research available on the extraction of polyphenols from coffee pulp and the results obtained in its application for insecticidal, fungicidal, and antibacterial control. At the same time, this review integrates the mentioned control strategies into a single analysis, allowing the identification of which applications (insect, fungal, or bacterial control) lack sufficient information. The purpose is to demonstrate that coffee pulp is a viable botanical pesticide and a sustainable alternative for Integrated Pest Management (IPM), as well as an environmentally friendly option for coffee-producing countries that generate large amounts of this agricultural residue annually.

BOTANICAL PESTICIDES

This classification is assigned to extracts of bioactive chemical compounds found in different parts of plants that act as repellents, anti-food, and growth inhibitors that have the potential to control pests (Ngegba et al., 2022). Botanical pesticides, in general, have been reported mainly in the management of insects, however, it has been shown that plants also have active compounds that have inhibitory effects on viruses, bacteria, fungi, and nematodes and that this control effect depends on the active compound that is extracted (Cardoso and Carmello, 2022; Lengai et al., 2020; Ngegba et al., 2022).

The specific bioactive compounds of each part of the plant and their abundance dictate how they will be isolated to be used as a botanical pesticide. In the case of polyphenols from coffee pulp, for example, extraction methods have been studied in search of process optimization, which is why it is proposed that the extraction efficiency and selectivity of the bioactive compounds that can be obtained from the pulp and, consequently, their respective biological activities depend on the method and the conditions of extraction (Cardoso and Carmello, 2022; Hu et al., 2023; Lengai et al., 2020).

These techniques fall into two categories: conventional methods, such as solid-liquid extraction, maceration, and Soxhlet extraction; and unusual techniques, such as enzymatic extraction, fermentation, supercritical fluids, ultrasound, microwaves, and eutectic solvents. Due to their ease of scaling, solid-liquid extraction ultrasonic and microwave-assisted technologies are the most popular; on a lesser scale, the other technologies are thought to be more generally utilized alternatives (Bondam et al., 2022; González-González et al., 2022).

Solid-liquid extraction is usually done by varying the solvent, time, and agitation, among the most common solvents for extracting polyphenols are water (Tran et al., 2020), methanol (Sangta et al., 2021), and ethanol (Kusumocahyo et al., 2020). However, it has the disadvantage that it requires high temperatures that incur energy costs and losses of volatile solvents (González-González et al., 2022).

Microwave and ultrasound-assisted methods have been implemented to overcome this limitation in solid-liquid extraction and thus expand the number of solvents that can be used while taking advantage of the effects of turbulence and cavitation (Kumar et al., 2021). Solvents such as methanol, ethanol, acetone, and propylene glycol have been used; however, these are usually used on a pilot scale or a small scale due to the volume of production that can be processed and the cost of the technology (Chen et al., 2021; Hu et al., 2023).

The importance of botanical pesticides is attributed to their efficacy, biodegradability, varied modes of action, low toxicity, availability of source materials, and short pre-harvest and re-entry intervals, which make them very attractive in organic agriculture and integrated pest management (Lengai et al., 2020).

The use of botanical pesticides has been primarily understood on a small scale because a mixture of compounds is typically extracted from plants, but not all of them have inhibitory activity, the heterogeneity of the extracts, the increase in purification costs, and the lack of information on the abiotic environmental impact, non-target organisms, and human health. Nevertheless, despite their advantages, botanical pesticides are not commonly employed because, as with any agricultural technology, institutional, socioeconomic, and knowledge variables must be considered before being applied on an industrial scale as an IPM strategy (Kabir et al., 2022).

POLYPHENOLS AS BOTANICAL PESTICIDES

Common bioactive compounds in botanical pesticides are mainly secondary metabolites such as steroids, alkaloids, tannins, terpenes, flavonoids, resins, and phenols that possess antifungal, antibacterial, antioxidant, or insecticidal properties (Lengai et al., 2020). In this sense, phenols are a set of substances that contain the hydroxybenzene group in their structure and polyphenols are the heterogeneous group within this category that also has several aromatic rings in its structure (Chaves-Ulate & Esquivel-Rodríguez, 2019), from which compounds such as tannins, terpenes, flavonoids, and chlorogenic acids are derived, which have demonstrated various properties mentioned above, currently being used in different areas such as biology, medicine, technology for food, and agriculture (Le et al., 2023; Murthy and Naidu, 2012; Solomakou et al., 2022).

The latter field includes testing the efficacy of polyphenolic extracts in pest management by applying them to small agricultural plots (Benaute et al., (2023). Strawberry production yield and its impact on Integrated Pest Management (IPM) were assessed using the polyphenolic extract, which produced favorable findings primarily in terms of insecticidal action when paired with chemical products. Thus, a balance between production yield and the reduction of applied chemical load was found, even if the chemical application of pesticides for control was not decreased.

COFFEE PULP AS A SOURCE OF POLYPHENOLS

The coffee fruit is primarily composed of thehusk, endocarp, pulp (mesocarp), skin (epicarp/exocarp), and two grains (Alves et al., 2017). According to Hu et al. (2023), the pulp is produced as the primary byproduct of wet processing fruit to extract only grains. It can account for 40–50% of the fresh fruit's weight. Among the remaining residues of the coffee fruit, the coffee husk is mainly composed of polysaccharides in cellulose and hemicellulose structures that together constitute approximately 40-45% of the dry weight of the husk (Machado et al., 2024), as well as the components of the dry endocarp which are mainly cellulose (40–49%), hemicellulose (25–32%), and lignin (33–35%), which is why it is mainly valued as fuel (Muñoz et al., 2019). Coffee mucilage is a highly hydrated viscous tissue composed of cellulose, pectin, and non-cellulosic polysaccharides, which are mostly removed with processing and remain in the wastewater (Siridevi et al., 2019).

The main components of coffee pulp are proteins (8–15%), lipids (2–7%), tannins (2–9%), carbohydrates (21–50%), caffeine (1–2%), chlorogenic acids (2–3%), and caffeic acid (2%) of dry weight. This composition makes coffee pulp a versatile raw material (Reichembach et al., 2024). Figure 2 shows the chemical structure of these mentioned compounds, which is relevant as it relates to the mechanisms of action in the pesticide activities of the extracts.

Total polyphenol content in coffee pulp has been reported to range from 2 to 10 g per 100 g of dried pulp; this range has been attributed to various factors, including the extraction method, the quantification method, and the species or geographic origin of the sample (Iriondo-DeHond et al., 2019; Machado et al., 2023).

Within the total polyphenols of Arabica coffee pulp, Sangta et al. (2021) classified the extracted polyphenols as flavonoids and non-flavonoids following the classification of Vladimir-Kneevi et al. (2012), and recorded that epigallocatechin gallate was the majority component in flavonoid compounds (31.8%) and caffeic acid in non-flavonoid compounds (68.1%). Similarly, Heeger et al. (2017) reported that chlorogenic acid, gallic acid, protocatechic acid, and rutin acid were the main compounds obtained from coffee pulp (together representing 80% of the total polyphenol content of the sample).

INSECTICIDAL ACTIVITY OF POLYPHENOLS IN COFFEE PULP

A wide range of crops are impacted by insects, including hydroponic systems, monocultures, organic crops, and ornamental plants (Arrieta and Azofeifa-Jiménez, 2018). Typically, chemical pesticides are applied as a control measure when insects attack crops. They can, however, disrupt integrated pest management (IPM) systems since they are typically non-selective and impact both beneficial and problematic organisms (Jurić et al., 2023).

Although chemical control is still the most common approach in these situations, the use of sustainable control methods, such as the use of botanical extracts as an alternative, is becoming more and more important as a fundamental strategy to reduce the negative effects on human health and the environmental impact caused by ingesting insecticide residues in consumer products (Lima et al., 2024; Isman, 2020).

Polyphenols, being secondary metabolites, play a fundamental role as a chemical defense of the plant against insects, given their composition these metabolites can be extracted and used as natural insecticides (Singh et al., 2021). The main compounds in this group play an important role in acting as growth regulators, anti-food, larvicide, and ovicide (Hernandez -Trejo et al., 2021; Ngegba et al., 2022).

Although a variety of polyphenolic compounds with these properties have been exposed,

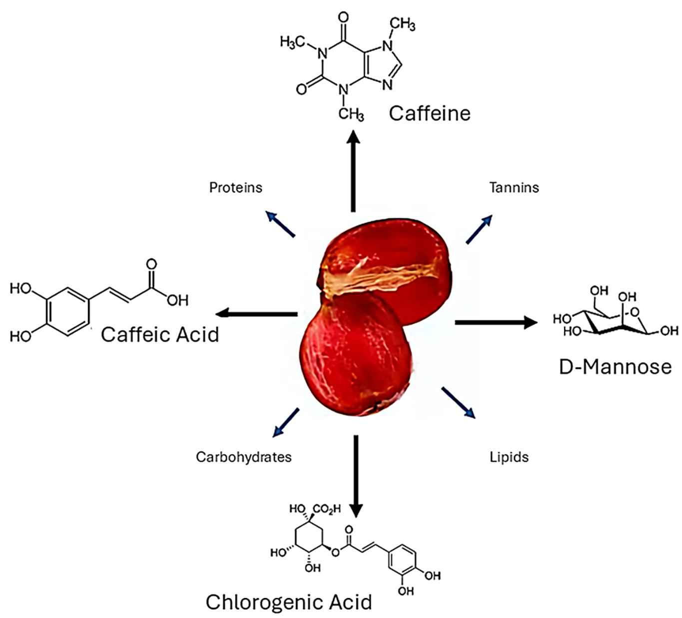

Figure 2. Chemical structures of the main polyphenolic compounds are obtained from coffee pulp.

concerning coffee polyphenols (Lengai et al., 2020; Ngegba et al., 2022; Singh et al., 2021) In *Coffea arabica* positive effects have been reported against phytophagous pests such as the southern green bug (*Nezara viridula*) and the brown marmorated bug (*Halyomorpha halys*) mainly because of the caffeine contained in the extracts (Jurić et al., 2023). Figure 3 shows the insect species being controlled and the chemical structure of the substance considered responsible for the control.

FUNGICIDAL ACTIVITY OF COFFEE PULP POLYPHENOLS

According to Pannu et al. (2024), pathogenic fungi are among the most prevalent infectious agents in plants and are responsible for large losses in agricultural productivity, both in terms of quantity and quality. The use of synthetic antifungal medicines has traditionally been the most popular method for preventing such losses. It is vital to look for natural antifungal alternatives with less of an impact on the environment and human health because some of these fungicides might cause fungus populations to become resistant and have negative environmental impacts (Sallach et al., 2021).

In addition to insecticidal and antibacterial activity, polyphenolic compounds are also known to be effective inhibitory agents of pathogenic fungi, due to their possible modes of action that include, among others, toxic effects, induction of apoptosis, inhibition of hyphae development, inhibition of biofilm formation and alteration of cell membrane integrity (Konuk and Ergüden, 2020; Sangta et al., 2021).

In the case of the polyphenols obtained from Arabica coffee pulp, Sangta et al. (2021) showed the effectiveness of the extracts against *Alternaria brassicicola*, fungi of the genus *Pestalotiopsis* and *Paramyrothecium breviseta*, attributing the inhibitory effect to caffeic acid and epigallocatechin gallate, which were the compounds most extracted. At the same time Ambriz et al. (2020), they found promising inhibitory results using arabica coffee pulp polyphenols in *Aspergillus niger, Botryris cinerea* and *Rhizopus stolonife*, attributing the antifungal activity to chlorogenic acid and caffeic acid present in the extracts

ANTIBACTERIAL ACTIVITY OF COFFEE PULP POLYPHENOLS

The most common method of treating bacterially contaminated crops is the use of antibiotics or bactericidal insecticides (Blanco-Meneses et al., 2023). Oxytetracycline, oxytetracycline and streptomycin combinations, and the aminoglycoside kasugamycin are some of the antibiotics used to manage these bacteria (Uribe-Lorío et al., 2024). Furthermore, as biocontrol agents, antagonistic organisms, including *Bacillus* bacteria, have been employed to cultivate phytopathogenic bacteria (Altindag et al., 2006).

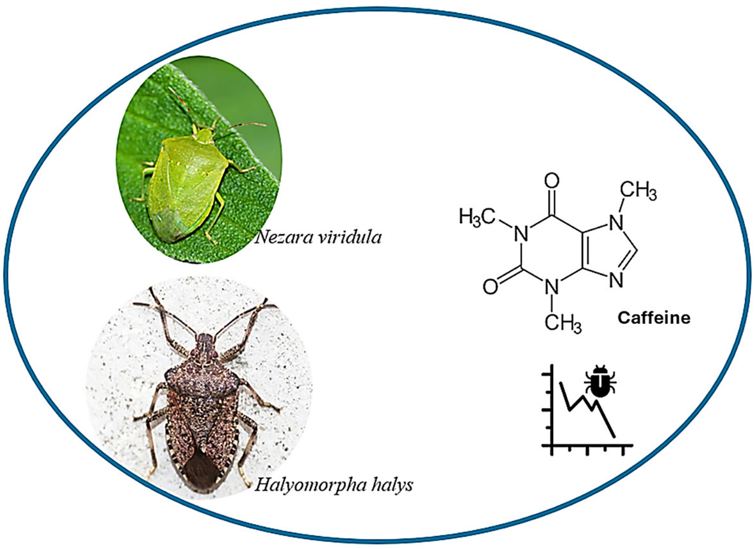

Figure 3. The compound responsible for the control of the southern green bug (*Nezara viridula*) and the brown marmorated bug (*Halyomorpha halys*)

The OMS views the use of antibiotics in agriculture as a public health issue that motivates the search for alternatives to treat bacteria. Bactericides have been used generally in pest control for all types of crops, with monocultures registering a greater use (Hassaan and The Nemr, 2020). Meanwhile, there is a latent concern about the use of antibiotics in agriculture due to the potential for resistance to spread (Uribe-Lorío et al., 2024).

In addition to being insecticides and possessing outstanding antioxidant properties, polyphenols have demonstrated significant antibacterial activity (Xu et al., 2018). Coffee pulp (*Coffea arabica*) contains polyphenolic compounds that have been studied for their antibacterial activity against *Staphylococcus* and *Escherichia coli*. The results showed that the active compounds, primarily caffeine, and chlorogenic acid, which were the most common extracts used, significantly inhibited the growth of bacteria (Duangjai et al., 2016).

Although the various mechanisms of action of polyphenolic compounds are known, they have not yet been fully understood. This is because of the structural diversity of polyphenols, which makes it impossible to predict the forces of interaction that each class of polyphenol will have with bacteria and the impact that each class of polyphenol will have on antimicrobial activity. According to Bouarab-Chibane et al. (2019), there may be an interaction between a few groups of the extracted polyphenols and the concentration that results. Not every chemical that is isolated can inhibit bacterial cells.

The interaction of polyphenols with nonspecific forces such as hydrogen bonds and hydrophobic effects, lipophilic forces, as well as through the formation of covalent bonds, has been linked to microbial membranes, although the antibacterial activity of polyphenols may also be due to the ability of these compounds to chelate iron, vital for the survival of almost all bacteria (Bae et al., 2022; Cueva et al., 2010; Papuc et al., 2017).

TOXICITY OF POLYPHENOLS

The harmful effects of polyphenolic compounds have only been partially documented because of their origin, the applications listed, and their diverse structures. The inhibitory and chelating properties of polyphenol botanical pesticides raise questions about whether they may endanger human health or the environment, despite their potential benefits in Integrated Pest Management (IPM).

As a consequence of this, research has arisen such as Chen et al. (2020) that showed the effect of low molecular weight polyphenols (phenolic acids) on nitrogen fixation, since due to the inhibitory capacity of this type of polyphenols, it was considered that it may affect the microorganisms responsible for this process in the soil; finding that low concentrations of phenolic acids in the soil during successive rotations of spruce cultivation led to reductions in nitrate content and an increase in ammonium content.

This is noteworthy since the polyphenols found in arabica coffee pulp extracts that demonstrated an inhibitory effect on the growth of bacteria and fungi are phenolic acids. While caffeic acid and chlorogenic acid have not been documented to exhibit this property, they should be considered for their potential use. However, the same researchers emphasize that while low molecular weight polyphenols can potentially break down and become a source of carbon, the effect is dependent on the microbes in the soil (Chen et al., 2020; Fierer et al., 2001).

Regarding the impact of polyphenols on health, it has been found that their ability to chelate iron and copper ions can be detrimental when these minerals are insufficient. Nevertheless, the concentrations of polyphenols that are deemed hazardous to human health are significantly higher than those found in the environment, and to harm health, polyphenols must be taken directly as supplements, demonstrating that they are not as dangerous as synthetic pesticides (Duda-Chodak and Tarko, 2023).

These factors have led to the use of polyphenols in general as a sustainable alternative in agriculture, either as supplementary compounds to reduce the overall chemical load applied to crops (Jablonska-Trypuć and Wind, 2022) or as a replacement for synthetic pesticides (Godlewska et al., 2021; Verhulst et al., 2023).

CONCLUSIONS

Coffee pulp is a promising raw material for use as a botanical pesticide due to the variety and number of chemical species found in its polyphenols, as well as how little it has been explored not only for this application but also as a general source of these substances. Its effectiveness against bacteria, fungi, and insects suggests that it has the potential to be a broad-spectrum agent. Although there are many advantages to using botanical pesticides, further study is required to determine the effects on the environment and human health, particularly concerning the unreported polyphenols in coffee pulps. For botanical pesticides to be used permanently, safely, and sustainably, research on polyphenols' impacts on soil microbes, nitrogen cycling, and human mineral intake is essential. Coffee pulp polyphenol-derived botanical insecticides are a practical and alluring substitute for conventional IPM methods. Advantages such as low toxicity, biodegradability, and various modes of action covering a wide spectrum of applications are highlighted. The control of insects in plantations to reduce the consumption of chemicals, and the application in the management of bacteria and fungi in a natural way without resorting to the use of pesticides or antibiotics that affect the abiotic components and non-target organisms present in agroecosystems make these compounds a viable alternative to reduce the use of harmful compounds and improve sustainable agriculture practices.

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