Revista Internacional de Investigación e Innovación Tecnológica

Página principal: www.riiit.com.mx

Valorization of coffee waste through its incorporation in the development of food biofilms-Review

Valorización de desechos de café a través de su incorporación en el desarrollo de bio-películas de alimentos-Revisión

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Technological innovation: The present manuscript described the valorization of coffee waste in the development of bio-packing for foods.

Industrial application area: Bio-packing Technology for food.

Received: may 26th, 2022
Accepted: february 01th, 2023

Resumen

En el mundo, los alimentos que se producen para consumo humano se pierden o desechan, tales como grupos de frutas, vegetales, raíces y tubérculos. De manera similar, una gran cantidad de residuos se generan en las agroindustrias, sin embargo, se puede obtener un valor agregado para reducir el impacto ambiental, por ejemplo, el bio-película tal como un recubrimiento o película comestible para incrementar la vida de anaquel de los alimentos con alta demanda en el mercado. Los principales compuestos bioactivos presentes en estos residuos son compuestos polifenólicos con actividades antimicrobianas y antioxidantes, los cuales son añadidos como nutraceúticos en alimentos funcionales. Particularmente, el café es el segundo producto que se comercializa en el mundo y genera grandes cantidades de subproductos y residuos durante su procesamiento. Por esta razón, esta revisión bibliográfica trata una visión general de los avances recientes en la valorización de los residuos agroindustriales y alimentarios utilizando sus compuestos bioactivos con aplicación como bio-películas y recubrimientos comestibles con enfoque en la revalorización de los residuos de café.

Palabras clave: residuos agroindustriales, bio-película, residuos de café, recubrimiento; película.

Abstract

In the world, food that is produced for human consumption is lost or thrown away, such as groups of fruits, vegetables, roots and tubers. Similarly, a large amount of wastes is generated in agro-industries, but value added can be obtained to reduce environmental impact, for example, biofilms such as edible coating or film to increase the shelf time of food products with high demand in the market. The main bioactive compounds present in these wastes are polyphenolic compounds with antimicrobial and antioxidant activities, which added as nutraceuticals in functional foods. Particularly, coffee is the second largest traded commodity in the world and generates large amounts of by-products and residues during processing. For this reason, this review is an overview of the recent advances in valorization of agro-industrial and food wastes using their bioactive compounds with an application as edible bio-films and coatings, with a focus on the re-valorization of coffee waste.

Keywords: Agro-industrial wastes, biofilms, coffee wastes, edible coatings, edible films.

Introduction

Worldwide, about one third of the food produced for human consumption is lost or wasted, with amounts 1.3 billion tons of food. In addition, the highest waste rates are concentrated in the root crops, fruits, vegetables and oilseeds groups with 40-50% (1). Food waste is related to a decrease in the quantity and quality of food. At the same time, waste is defined as safe and nutritious food that is discarded or used in non-food alternatives throughout the supply chain (2). Particularly, agro-industrial waste has been used as raw material in several processes for value-added products such as edible films and coatings. The agro-industrial waste comprise essentially stalks, peels, seeds and cracked pulp which still contains large amounts of bioactive molecules and biopolymers, among them polyphenols, antimicrobial compounds and antioxidants (3–5). This agro-industrial waste represents an excellent alternative for the natural source, which translates as renewable, recyclable and degradable sources and they offer the opportunity to reduce costs. Furthermore, food waste is referred to as the decrease of edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption the main reason for obtaining of these wastes are mechanical stresses, physiological disorders and decays (6). As fresh products have a short shelf life, the use of appropriate packaging is recommended. At present, synthetic preservatives (antimicrobials and antioxidants) have potentially adverse effect on consumers, and making many bioactive compounds from agro-industrial waste an interesting alternative. Biofilms such as edible coatings and films have shown to increase the shelf time of products with high market demand. Some natural raw materials have been used for edible coatings and films. Specially, by-products of the coffee industry (coffee pulp and husk) have potential biotechnological applications. Coffee pulp and husk are the by-product with the greatest impact on environmental pollution from the coffee industry. These materials represent approximately 30% dry weight of the whole berry.

Since coffee pulp from the wet processing of coffee beans is a potential source of antioxidants, mainly tannins. Tannins can form insoluble complexes with carbohydrates and proteins and are responsible for the astringency of tannin-rich foods, because of

the precipitation of salivary proteins (7). Besides they are toxic for fungi, bacteria and yeasts (8).

This review explains the importance of using agro-industrial coffee waste for obtaining edible films, coatings and their application in tropical fruits (mango, papaya, pineapples, and bananas, among others) to increase the shelf time life.

Agro-industrial and food waste

In the agroindustry, raw materials are processed to obtain value-added products, however a high of waste is inevitable, which is the main environmental problem. But waste is exploited in other areas and news added values are generated. In addition, food losses and waste cause pollution of natural resources as such as water, soil, energy, workforce and capital, including unnecessary greenhouse gas emissions that promote global warming and climate change. Equivalently, food waste represents roughly one-third parts of the food produced for human consumption with losses of about 1.3 billion per year of which 0.5 t correspond to fruits and vegetables. Mainly, in developing countries, fruit and vegetables waste are severe during agricultural processing, accounting for 25-40% of losses (2). In addition, low percentages of biomass are used in the agroindustry. In the brewing industry, 8% of the grain nutrients, in the palm delta 9%, in the coffee industry and 9.5% in the fresh delta. While in other industries about 30% as used in the pulp and paper industry, among other (9).

Currently, multiple applications of agro-industrial waste have been derived from its use as a renewable resource to obtaining products that protect the environment, including biodegradability. These wastes compress stalks, peels, seeds and crushed pulp, which contain numerous bioactive compounds and biopolymers, as well as considerable nutritional loss (10). Food waste result from a decrease in the edible mass food during the production, postharvest and processing stages in the edible food supply chain for human consumption (11). Specially, it is important to promote the reduction of food waste since whole plant tissues have been used which has led to the maximum exploitation of food raw materials (4). Although minimally processed foods and fresh fruits and vegetables have been increasing in demand due to consumer preferences, these products have a short shelf life, which is mainly attributed to mechanical stresses as well physiological disorders and decay, wastes are often discarded (6,12). Therefore, several researches focus on methods for decreasing the negative effects on the products quality such as the presence of microorganisms, the development of off-flavor, browning and texture breakdown. These interests benefit the distribution of fresh fruits and vegetables. However, the extensive use of synthetic packaging is the origin of serious ecological problems due to its total non-biodegradability, but investigations are developing to decrease this behavior (13).

Edible films and ~~edible~~ coatings: what are the differences?

Food microbiological contamination is a serious problem in modern society, since food-pathogen interaction concurrent foodborne pathogens can also be developed by the food itself through degradation (21). An alternative solution is the use of appropriate packaging, since it acts as a barrier and can protect food from pollution. The packaging reduces the contact of food with atmospheric agents (oxygen and water vapor) that promote the microbial proliferation. In addition, the moisture migration can affect product quality and shelf life that causes husk browning and thus reduces the commercial value (14,15).

Several studies have suggested that biofilms such as edible films or edible coatings, which are able of preserving quality attributes and extending the shelf life of fruits. An edible coating is defined as a thin layer of edible material that is formed as a covering surface on a food product, an edible film is a pre-formed thin layer which once formed can be placed on food (16). The main difference between these packages is that edible coatings are used in liquid form by immersing or spraying on the product, whereas edible films are molded as solid sheets and then applied as a wrapping on food (16). These techniques have been applied on fruits such as acerolas (*Malpighia punicifolia* L.) (17), litchi (*Litchi chinensis*) (18), and mandarins (*Citrus reticulata* Blanco), oranges (*Citrus sinensis* [L]. Osbeck) (19), among others.

In edible films compositions, the use of one or more components is necessary to generate a polymeric network with appropriate physical properties that are strongly dependent on the nature and chemical interaction of the resulting structure. There are reported on the use of polysaccharides, lipids and proteins in these formulations (17,20). For achieving film functionality compatible with those of traditional film-forming materials (whey protein isolate, chitosan, and starch), additional pectins and plasticizers were incorporated into the extracts. Pectin is a complex anionic polysaccharide composed mainly of 1,4-linked D-galacturonic acid units and its methyl ester, is a potential film-forming material and miscible with polymers (21). Recent works appear to use the blends of pectin with other polysaccharides to make edible films, such as polyvinyl alcohol, starch, gelatin, hydroxypropyl methylcellulose, ethylcellulose (19) chitosan (18,22), have been investigated. Hydrophilic materials may therefore act as drug release regulators in mixed film coatings.

The use of edible films is likely to expand in the future, especially in the fruit and vegetable sector, since health-conscious consumers look for more foods requiring minimal preparation, such as cut fruit or premixed salads and to preserve the taste, aroma and appearance in food (23,24).

Application of bioactive compounds from agro-industrial wastes as edible films and coatings

Agro-industrial wastes from plants, fruits and vegetables are rich in their composition, for example polyphenols, are a class of chemical compounds with antimicrobial and antioxidant activity, which could be used to minimize food waste (3,5,25). Studies have reported the utilization of agro-industrial waste to generate edible films and coatings through the recovery of their bioactive compounds (26). Indeed, there is a growing trend in fruits and vegetables packaging sector to replace the petrochemical based packaging films with more environmentally-friendly biodegradable materials (27,28). Thus, new biological sources suitable for coating and edible film formulations are being researched. In this sense, fruit and vegetable solid wastes present potential benefits for use as packaging material matrices, since they are produced on a large scale and their exploitation could convert vegetable wastes into value-added or functional products. Such edible films and coatings would bring additional benefits to traditional edible film forming materials by conditioning the unique flavor and color of the fruit. Recently, any protective compound of fruit or vegetable residues on apple (*Malus domestica* var. Anna), acerolas (*Malpighia punicifolia* L) and strawberry (*Fragaria X ananassa* Duch.) have been premised on reducing microbial load and maintaining postharvest quality (17,26), where a sensory analysis is interesting to evaluate the coating in a way that does not change both taste and

flavor in the final product (29). Biologically-based film and coatings contain raw materials originating from agricultural sources, produced from renewable raw materials such as starch and bio-derived monomers. The use of agro-industrial waste by-products has obvious economic and environmental advantages.

Main bioactive compounds in plants

In the past few years, much attention has been paid to bioactive compounds due to their ability to promote human health benefits, such as the reduction in the incidence of some degenerative diseases like cancer and diabetes (30). Bioactive compounds are additional nutritional constituents that naturally occur in small quantities in plant and food products. A significant number of phenolic compounds, including anthocyanins (derived from delphinidin, cyanidin and pelargonidin), hydrolysable tannins (catechin, epicatechin, punicalin, pedunculagin, punicalagin, gallic and ellagic acid esters of glucose), have been reported (31) with antioxidant and antimicrobial capacities.

Interestingly, phenolic compounds or polyphenols are present in all plants and have been extensively studied in cereals, legumes, nuts, olive oil, vegetables, fruits, tea, red wine and others. There can use as food additives for preserving fruits and vegetables. In addition, olive oil is reported to contain both phenolic acids and hydrolyzable tannins. As well as *Larrea tridentata* and *Flourensia cernua*, endemic plants of Mexican Semi-desert. Research groups of tannins focused on the chemical structure and diversity of the tannins and their biodegradation, trying to develop bioprocesses that allow the biotransformation of the tannins present in some Mexican plants and produce important phenolic bioactivities (32). Interestingly, phenolic compounds provide antioxidant activity, which are responsible of preventing the formation of free radicals. In food, these compounds prevent rancidity and retard the formation of toxic oxidation products, which impacts upon the maintaining of nutritional quality and extends the shelf-life of products. Antioxidant activity contributes to the nutritional quality of food and to human health benefits (33). In addition, food such as both cocoa powder, chocolate (34), mandarin oranges, apple, papaya, pineapple and mango have antioxidant activity (10). Thus, the total antioxidant capacity of an edible vegetable product could be a parameter to evaluate the quality of plant foods.

It is well-known that bioactive compounds possess antimicrobial activity. Bioactive compounds extracted from plants or agro-industrial wastes have great potential as novel fungicide sources for controlling pathogenic fungi (35). Antimicrobial packaging has emerged as a potential means to assist the preservation and extend the shelf life of perishable foods, reduce moisture loss and enhance flavor and color (36). Previous studies have confirmed that the antimicrobial compounds content give many wastes (Table 1).

Table 1. Inhibitory effect of phenolic compound extracts used in biofilms from waste under the microbiology growth of any microorganism used in biofilms.

Inhibited microorganism	Wastes/Fruit	Author
Fusarium spp.	Hojasén leaves (*Fluorensia cernua*)	(37)
Staphylococcus aureus	Walnut (*Juglans regia L.*) green husks	(38)
Fusarium oxysporum	Pomegranate husk *(Punica granatum)* and pecan nut shell *(CaryaIllinoensis)*	(35)
Listeria monocytogenes	Pomegranate (*Punica granatum*) peel extract in meat paté	(39)
Escherichia coli, Pseudomonas aeruginosa, Salmonella sp., Staphylococcus aureus and Listeria monocytogenes	Pulp of tamarind (*Tamarindus indica L.*)	(40)
Escherichia coli and *Staphylococcus aureus*	Silver nanoparticles using dried roasted coffee arabica seed extract	(41)
Mesophilic bacteria	*Aloe vera*	(41)

According to Lira-Saldívar *et al.*(42), the extract of *Larrea tridentata* Cov. was effective against *Pythium* sp. In addition, Ventura-Sobrevilla *et al.*(37) reported the extracts of *Fluorensia cernua*, *Jatropha dioica*, *Turnera diffusa,* and *Euphorbia antisyphilitica* were effective against some important fungi, which include *Penicillium purpurogenum*, *Fusarium* spp. *Rhizoctonia solani,* and *Aspergillus flavus*. The development of coatings which use antimicrobial agro-industrial wastes as a support matrix is very promising (23).

Several categories of antimicrobials can be potentially incorporated into edible films and coatings, including organic acids (acetic, benzoic, lactic, propionic, and sorbic), fatty acid esters (glyceryl monolaurate), polypeptides (lysozyme, peroxidase, lactoferrin, and nisin) and polyphenols. In general, organic acids incorporated in films did not adversely affect the sensory properties of coated fruit (43).

The use of agro-industrial waste as potential sources of this kind of bioactive compounds, which represent an attractive alternative to produce extracts with a broad spectrum of antifungal activity (32). In this sense, many tannin-rich plants such as fruits and vegetables from Mexico have in most cases an unknown and well-defined pool of phytochemicals with antimicrobial potential to be used against pathogenic fungi (42). However, multiple research has been conducted to clarify this point. Next, speaking about bioactive compounds, an important area that produce great amount of waste is coffee. For this reason, the information is explained in the following lines.

Coffee wastes: a promising source of bioactive compounds

Coffee is one of the world's most important crops and Brazil is the world´s largest producer with 2, 804, 07 t with 10.5 million of hectares planted (44). Over the past few

years, both production and consumption of coffee have increased considerably. Consumers have reaped some of the benefits through a greater variety of coffee products, improved quality and lower prices. Now more than 70 countries produce coffee, with over 50 percent coming from just three countries (2). *Coffea arabica* (cherry coffee) and *Coffea robusta* (or *Coffea canephora*) are the two principal varieties of the genus cultivated worldwide for commercial production (45). Coffee is the second largest traded commodity in the world and generates large amounts of by-products and waste during processing (46). According to the International Coffee Organization (ICO) world coffee production has increased in the last few years. During 2020-2022 coffee production was 172 million of bags (60 kg/ bag) approximately, an increase of 5% compared to the period 2017-2021 (47). Mexico is one of the most important *C. arabica* producers and the largest coffee harvesting area worldwide (2). Mexico is ranked eleventh in the world with a production of 218 927 t. The United States and Spain are the principal buyers with 54.3 y 12.3% of green coffee (70). This high production generates thousands of tons of waste per year and its revaluation has not been exploited yet. This waste is considered an important source of pollution by coffee growers.

Structurally, the coffee berry or coffee cherry consists of the pericarp, mucilage, endocarp, silver skin and coffee bean. The pericarp, also called skin, is usually green in unripe fruits but that turns red when ripe. In addition, inside of the pericarp is the yellowish, fibrous and sweet pulp or outer mesocarp. This is followed by the mucilage, which is translucent and is called pectin layer. Then there is the endocarp or parchment, finally the silver skin in the middle of the fruit which cover each coffee bean (48).

Agro-industrial Coffee Waste

The coffee wastes represent a serious environmental problem for coffee producing countries. For every ton of coffee cherry, nearly 0.18 ton of coffee husk is generated (49). The wastes can be used for industrial applications such as the production of high-quality biodiesel, the cosmetic application of the extracted oil, prevention of the harmful effects of UV radiation on the skin (50), fertilizer, compost (10), bio-sugar and bioethanol production and animal feed. Coffee pulp and husk are by-product with the greater contribution to environmental pollution from the coffee estates, where coffee pulp can be pollutants fresh water. However, coffee pulp has economic implications that may become evident as its use increased (51). This material is the main residue obtained during wet and semi-dry processing and represents 30% of the dry weight of the whole berry (52) (Table 2).

Previous studies revealed different compositions of coffee by-products, including coffee pulp, which is composed by carbohydrates (50%), fiber (20%), protein (10%), fat (2.5%) and caffeine (1.3%), including phenolic compounds and tannins (46). The total concentration of phenolic compounds in fresh coffee pulp was reported to be 37.9 g/kg. In addition, coffee pulp is a potential source of antioxidants which should not be wasted, due to abundance of chlorogenic acids (53). The phenolic compounds and antioxidant activity depend directly of the extraction method: aqueous infusion (52), methanol/water extraction or acidified aqueous methanol (54). On the other hand, coffee husks are composed of the outer skin of the berry, pulp and parchment, mainly resulting from the coffee dry processing. They are rich in carbohydrates (35%), fibers (30.8%), minerals (10.7%), proteins (5.2%), (55), chlorogenic acid (2.6%) and caffeic acid (1.6%) (46).

Table 2. National and global production of coffee cherry by-product (56).

Coffee cherry	Tons / year	Subproduct (30%) / year
Mexico	1,352,988 tons	405,896 tons
Global	14,357,142 tons	4,407,142 tons

Several extraction methods of bioactive compounds have been developed (Table 3), but with different extraction yields, including water/methanol treatment and water/ethanol mixtures have been shown to give higher extraction yields than water for different agricultural wastes (57). At the same time, the content of phenolic compounds in pulps from different plantations will vary but they all contain phenolic compounds, and are an efficient antioxidant. However, their properties are not limited to antioxidant activity, but they can also provide antiallergic, anti-inflammatory and antimicrobial effects. Since Pandey *et al.* (45) reported the presence of condensed tannins in coffee pulp, many studies were derived, demonstrating that coffee pulp has antimicrobial activity against bacteria such as *Staphylococcus aureus*, *Enterococcus faecalis*, *Bacillus subtilis*, *Pseudomonas aeruginosa*, and *Escherichia coli*, mainly (58).

Table 3. Bioactive compounds from coffee wastes and application in the food

Material	Bioactive compound	Method of extraction	Antioxidant activity	Antimicrobial Activity	Application	Reference
Roasted coffee beans (*Coffea arabica* L.)	Caffeine and chlorogenic acid	Aqueous	ND	*Proteus hauseri*	NS	(58)
Coffee pulp	Polyphenolic compounds Hydroxycinnamic acid	Fermented with *Aspergillus tamarii*, or no fermented aqueous-metanol	Fermented extracts with the major antioxidant activity	ND	NS	(54)
Coffee pulp extract	Total phenolic compounds (mg/L of acid gallic) CPE1: 17.4 CPE2: 10.47 CPE3: 7.61 Chlorogenic acid, and caffeine in CPE1	Aqueous extracts. CPE1 (washing, removing, drying and blending) CPE2 (washing, selecting, removing, drying and blending) CPE3 (washing, selecting, removing**,** freezing**,** drying and blending**)**	ABTS (IC50 µg/mL) CPE1: 18 CPE2: 27 CPE3: 27 DPPH (IC50 µg/mL) CPE1: 82 CPE2: 153 CPE3: 140	Efficiency of CPE1 *Staphylococcus aureus* *Staphylococcus epidermidis* *Pseudomonas aeruginosa* *Escherichia coli*	NS	(59)
Coffee cherry pulp	Caffeine and polyphenols	Aqueous	8.86 ORAC (mmol TE/L)* 3.02 ABTS (mmol TE/L)* 283 TPC (mg of GAE/L)*	NS	Cascara beverage production	(52)
Spent coffee ground	Total phenolic compounds	Ultrasonic	0.36-0.51 DPPH (mmol TE/g dried SCG). 0.39-0.76 ABTS+ (mmol TE/g dried SCG)	*E. coli* *S. auereus*	NS	(60)
Spent ground coffee (dark roasted degree)	Total phenolic compounds (5.66 mg GAE/g	Aqueous	80.5% ABTS	Absence phytopathogenic fungi or foodborne pathogenic bacteria	Alternative as natural herbicide	(8)

***** Detected in cascara beverage, ND=not determined, NS=not specified, CPE=coffee pulp extract, ABTS= 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulphonic acid), IC50=half maximal inhibitory concentration, SCG=Spent coffee ground, ORAC=Oxygen Radical Absorbance Capacity, TE=Trolox equivalent, TPC= total phenolic content, GAE=gallic acid equivalents.

Perspectives of bioactive compounds from coffee waste as bio-packing systems

Nowadays, multiple benefits of bioactive compounds from coffee waste has been described and several researches have focused on environmental points for bioethanol production. In addition, coffee waste has been demonstrated to be an excellent alternative for treatment of obesity and type 2 diabetes since a functional beverage can be formulated with these waste(61). However, their application as films and coatings is an excellent alternative with the aim of increasing shelf life extension due to the comments mentioned in the previous lines, since the coffee wastes are rich in polyphenolic compounds with antioxidant and antimicrobial activities. A new functionality was observed in the incorporation into a carboxymethyl cellulose-based film as changes in its properties as well as color and opacity, improved the light barrier of the film and provided an enhancement or at least a preservation in the physicochemical properties.

Pectin from coffee mucilage has been applied for the generation of degradable films. In addition, pectin and cellulose from coffee pulp have been used to produce biopolymers films (62). Polysaccharides from spent coffee grounds polysaccharides (galactomannans) are an excellent alternative for edible films too (63).

Acknowledgements

PRODEP-SEP for funding the project ITCVAL-PTC-003.

Conflict of interest

The authors declare that they have no conflict of interest.

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