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Fermentation of agro-industrial by-products as a strategy to obtain quail feed additives

Fermentación de subproductos agroindustriales como estrategia para obtener aditivos para alimento de codorniz

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ABSTRACT

Agro-industrial activity in Mexico generates a significant amount of vegetable by-products (37.5 Mt, estimated production), which are generated during the processing of harvested fruits. These agro-industrial by-products are an essential source of nutrients and bioactive compounds that can be reevaluated. In this manuscript, the findings of different investigations are reviewed, in which the use of solid-state fungal fermentation (SSF) for the recovery of compounds from agro-industrial by-products with possible use as ingredients in quail feed is evaluated. Concerning the chemical composition of agro-industrial by-products will depend on the plant species, anatomical region (peel, pulp, and seed), and processing conditions (fresh or dry). These by-products have bioactive components, such as enzymes, vitamins, organic acids, pigments, and phenolic compounds (phenolic acids and flavonoids). As an alternative to conventional and unconventional extraction methods, SSF is a novel method for recovering bioactive components from agro-industrial by-products of crops, such as apple, wheat, corn, cassava, rice, potato, pomegranate, blueberry, chickpea, and orange. The bioactive components recovered by SSF are an alternative with potential use as additives for quail feed.

Keywords: agro-substrates, chemical composition, extraction methods, fungal fermentation, bioactive feed ingredient.

RESUMEN

La actividad agroindustrial en México genera una cantidad importante de subproductos vegetales (37.5 Mt, producción estimada), los cuales son generados durante el procesamiento de los frutos. Estos subproductos agroindustriales son una fuente importante de nutrientes y compuestos bioactivos que pueden ser revalorizados. En el presente manuscrito se revisan los hallazgos de diferentes investigaciones en las que se evalúa el uso de la fermentación fúngica en estado sólido (FES) para la recuperación de compuestos de subproductos agroindustriales, con posible uso como ingredientes en el alimento para codorniz. En relación a la composición química de los subproductos agroindustriales, ésta dependerá de la especie vegetal, región anatómica (cáscara, pulpa y semilla) y condiciones de procesamiento (fresco o seco). Estos subproductos poseen componentes bioactivos, como enzimas, vitaminas, ácidos orgánicos, pigmentos y compuestos fenólicos (ácidos fenólicos y flavonoides); como alternativa a los métodos convencionales y no convencionales de extracción. La FES es un método novedoso para la recuperación

de componentes bioactivos a partir de subproductos agroindustriales de cultivos, como: manzana, trigo, maíz, yuca, arroz, patata, granada, arándano, garbanzo y naranja. Los componentes bioactivos recuperados por FES son una alternativa con uso potencial como aditivos para el alimento de codorniz.
Palabras clave: agro-substratos, composición química, métodos de extracción, fermentación fúngica, ingrediente alimentario.

INTRODUCTION

In 2019, poultry production in Mexico was around 3.6 M metric tons, and presented a domestic consumption of 4.5 M metric tons; therefore, it is considered one of the main poultry producers in Latin America. However, the increase in poultry consumption has led to the import of approximately 0.9 M metric tons of chicken meat from other markets (USDA, 2019). Such an increase has caused an increase in the consumption of other small poultry species (Mnisi & Mlambo, 2018).

In this context, the Japanese quail (*Coturnix japonica*), is a small bird produced under an intensive system; mainly in European and Latin American countries, in order to obtain meat and eggs for consumption (Figure 1). The production of these birds is characterized by faster growth rate, early sexual maturity and low space requirements (Ghasemi-Sadabadi *et al*., 2020; Mnisi & Mlambo, 2018).

Figure 1. Japanese quail production system (source, Vargas-Sánchez Rey)

The intensive quail production system requires certain nutritional aspects, which are obtained from agro-industrial crops, such as soybean and corn; however, this depends on their availability and cost in the market (Mnisi & Mlambo, 2018). In this context, according to NRC (1994), the quail diet must be balanced to a specific energy level; in addition to having a certain content of protein, amino acids (mainly lysine, methionine, methionine+cysteine, arginine and threonine) and fatty acids (linoleic acid). It also requires minerals (calcium, non-phytate phosphorus, sodium, copper, iron, manganese and zinc) and vitamins (A, D, E, thiamine, riboflavin, pyridoxine, B12, folic acid, niacin, pantothenic acid and choline). However, the use of these components will depend on the age of the birds, the climatic zone and whether they are intended for meat or egg production (Mnisi & Mlambo, 2018; NRC, 1994).

Previous research has reported that agro-industrial by-products, including pulps, seeds and shells, are considered an important source of nutritional and bioactive components (Dong *et al*., 2014; Friedman *et al*., 2017; Gazalli *et al*., 2013; Kruczek *et al*., 2017; Rosero *et al*., 2019; Saleem y Saaed, 2020; Scully *et al*., 2016). These by-products have been incorporated as ingredients directly into quail feed to improve yield and meat quality (Ghazaghi *et al*., 2014; Mnisi y Mlambo, 2018). The bioavailability of these nutrients and bioactive compounds is limited, and depends on the matrix of the agro-industrial by-product used, which could reduce their digestibility and absorption in the bird's intestine (Cullere *et al*., 2016; Mnisi y Mlambo, 2018). Therefore, for the recovery of these nutrients, it is essential to establish strategies by using different recovery or extraction methods (Azmir *et al*., 2013; Rajavat *et al*., 2020). Therefore, a novel strategy for the recovery of these nutrients and bioactive compounds is solid-state fungal fermentation (SSF), which is carried out in a solid matrix (substrate). In the absence or near absence of free water; although the substrate requires moisture to support the growth and metabolic activity of the fungus (Chawla *et al*., 2017; Wang *et al*., 2019).

Therefore, the aim of the present research is to document the use of SSF as a strategic method to recover nutritional and bioactive components from agro-industrial by-products, and the possible use of these as feed additives for quail.

Agroindustrial by-products in Mexico

The Mexican territory has a total surface area of approximately 196.4 million hectares (MH), of which 21 million are destined for agricultural use (6.5 MH irrigated and 14.5 MH rainfed). In addition, the climatic and soil diversity of this country allows the development of a wide variety of crops, of which some are destined for direct trade and others are destined for the export market (SAGARPA, 2015). Of the various agricultural products grown in Mexico, the main ones are corn, beans, wheat, rice, sorghum, sugarcane, oilseeds, soybeans, safflower, sesame, coffee, chili, strawberry, peanuts, among others (Mussatto *et al*., 2011; SAGARPA, 2015; Valdez-Vazquez *et al*., 2010). However, derived from agroindustrial activity, a large amount of waste is generated, from plastics and metallic, to chemicals and vegetables (SAGARPA, 2015). Plant residues, also known as agroindustrial by-products can be divided into two main categories: primary or residues left in the field after harvest (e.g., straw/stem) and secondary by-products or residues generated when processing harvested crops (e.g., cobs, husks, pulps, and bagasse) (Valdez-Vazquez *et al*., 2010). Although the exact volume of agroindustrial by-products generated in Mexico is unknown, efforts have been made to estimate their production (Figure 2).

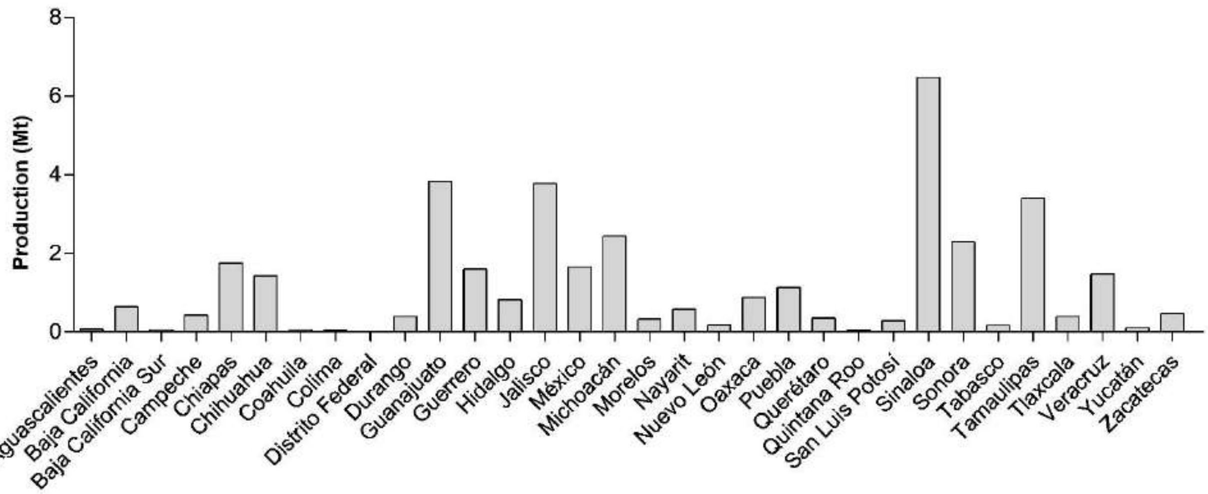

Figure 2. Production of agroindustrial byproducts in Mexico, 2008-2011 (SAGARPA, 2015)

In Mexico, the main by-product producing regions are as follows: in the northwest of the country, the municipalities of Ahome, Angostura, Culiacán, Guasave, Navolato, Sinaloa de Leyva (Sinaloa), Cajeme, Etchojoa and Navojoa (Sonora) and Mexicali (Baja California) are included. In addition, the municipalities of Cuauhtémoc (Chihuahua), Matamoros, Reynosa, Río Bravo, San Fernando, and Valle Hermoso (Tamaulipas) have also been considered high by-product production areas. In central Mexico, La Barca and San Martín Hidalgo (Jalisco), and in southern Mexico, Venustiano Carranza (State of Chiapas), Hopelchen (Campeche), Othon P. Blanco (Quintana Roo), and San Martin Hidalgo (Jalisco). Blanco (Quintana Roo), Tuxtepec, Acatlán de Pérez Figueroa, San Juan Bautista (Oaxaca), and the municipalities of Cosamaloapan de Carpio, Pánuco and Tres Valles (Veracruz), have been considered strategic areas for obtaining agroindustrial by-products (Valdez-Vazquez *et al*., 2010).
However, there are legal loopholes in the country that do not allow establishing a clear regulation for their reduction or reuse (SAGARPA, 2015). Despite the above, in Mexico the use of agroindustrial by-products is of special interest due to their availability, low cost and their components (nutrients and bioactive compounds); which could be considered

as an alternative for obtaining ingredients with potential for their incorporation in animal feed (SAGARPA, 2015; Valdez-Vazquez *et al*., 2010).

Chemical composition of agroindustrial by-products

The chemical composition of agroindustrial by-products is variable, and depends on the natural source (plant species), anatomical region (pulp, peel and seed) and processing conditions (fresh or dry). The approximate chemical composition of some agro-industrial by-products is shown in Table 1. The main components of agro-industrial by-products are proteins, carbohydrates and fats (Gazalli *et al*., 2013; Kruczek *et al*., 2017; Mussatto *et al*., 2011); while in smaller proportion are ashes (Kruczek *et al*., 2017; Talabi *et al*., 2016). On the other hand, dry matter content is highly variable and depends on the heat treatment conditions, since this parameter increases in plant material during heat treatment due to water loss (Gazalli *et al*., 2013; Mussatto *et al*., 2011).

Table 1. Nutritional composition of some agro-industrial by-products

Material	By-product	Composition	Reference
Apple	Dry pulp	Proximal composition: CH (3.9-10.8%), CP (2.9-5.7%), CG (1.2-2.9%), CC (0.5-6.1%), CCH (48.0-62.0%), and CF (4.7-51.1%). Fatty acids: C16:0, C18:0, C18:1, C18:2, and C18:3 Minerals: P, K, Ca, Na, Mg, Cu, Zn, Mn, and Fe Sugars: Glc, Fru, Xil, Man, Gal, Ara, and Ram	Kruczek *et al.* (2017)
	Dry pulp	Amino acids: Ser, His, Ala, Gly, Tyr, and Cys Sugars: arabinose, glucose, fructose, and sucrose	Dadwal *et al.* (2018)
	Dry seed	Amino acids: His, Gly, Tyr, and Cys Sugars: Ara, Glu, Fru, and Sac	Dadwal *et al.* (2018)
	Dry pulp	Proximal composition: CP (5.1%), CG (3.1%), CC (5.1%), and CF (24.7%)	Gazalli *et al.* (2013)
Avocado	Dry seed	Proximal composition: CH (26.3%), CP (6.3%), CG (16.8%), CC (5.2%), CCH (67.7%), and CF (4.0%) Minerals: Ca, Na, K, and P Vitamins: A, C, and E	Talabi *et al*. (2016)
	Fresh pulp	Proximal composition: CH (72.3%), CP (2.0%), CG (15.4%), CC (1.7%), CCH (8.6%), and CF (6.8%) Fatty acids: C16:1, C18:1, and C18:3 Minerals: Ca, Fe, Mg, P, K, Na, Zn, Cu, Mn, and Se Vitamins: A, C, K1, B2, B3, B5, B6, and B12	Dreher & Davenport (2013)
	Fresh peel, pulp and seeds	Proximal composition: CH (76.0, 77.4 y 55.8%, respectively), CP (1.8, 1.8 and 2.2%), CG (1.0, 15.8 and 1.4%), and CC (0.9, 1.0 and 0.7%)	Rodríguez-Carpena *et al.* (2011)
Carrot	Dry pulp	Proximal composition: CP (6.2%), CG (2.4%), CC (4.0%), and CF (20.1%)	Gazalli *et al.* (2013)
Coffee	Dried coffee bagasse	Minerals: K, P, Mg, Ca, Mn, Cu, Na, Fe, and Zn Sugars: Man, Gal, and Glc	Scully *et al*. (2016)
	Dry pulp	Amino acids: Ala, Arg, Asp, Cys, Glu, Gly, His, Ile, Leu, Lys, Met, Phe, Pro, Ser, Thr, Tyr, and Val	Campos-Vega *et al*. (2015)
	Coffee bagasse	Fatty acids: C12:0, C14:0, C18:0, C16:1, C18:1, C18:2, and C18:3	Campos-Vega *et al*. (2015)
	Dry coffee husk	Proximal composition CP (18.6%), CG (2.2%), CC (7.0%), and CF (62.4%) Sugars: Xil, Ara, Gal, and Man	Mussatto *et al.* (2011)
	Coffee bagasse	Proximal composition CP (13.6%) and CC (1.6%) Sugars: Ara, Gal, and Man	Mussatto *et al.* (2011)

Grape	Pomace skin	Proximal composition CP (6.5-12.3%), CG (1.1-6.3%), CC (3.3-7.2%), CCH (1.4-77.5%), and CF (28.0-56.3%) Sugars: Xil, Gal, Ara, and Man	Deng *et al*. (2011)
	Pulp and fresh stem	Proximal composition CH (53.9 and 61.5%, respectively), CP (3.8 and 2.2%), CG (0.5 and 0.9%), CC (2.1 and 4.3%), CCH (2.4 and 2.9%), and CF (37.4 and 28.8%) Sugars: Ram, Fuc, Ara, Xil, Man, Gal, and Glc	González-Centeno *et al*. (2010)
Lemon	Dry peel	Minerals: Cd, Cr, Cu, Fe, Mn, Mg, and Zn	Saleem & Saeed (2020)
	Peel	Vitamins: vitamin C	M´hiri *et al*. (2017)
Tangerine	Peel	Vitamins: vitamin C	M´hiri *et al*. (2017)
Orange	Dry peel	Minerals: Cd, Cr, Cu, Fe, Mn, Mg, and Zn	Saleem & Saeed (2020)
	Peel and dry seed	Proximal composition CH (9.7 and 8.3%, respectively), CP (11.0 and 6.8%), CG (6.3 and 0.8%), CC (4.9 and 3.0%), CCH (54.2 and 67.8%), and CF (14.0 and 3.0%)	Egbuonu & Osuji (2016)
	Dry peel	Proximal composition CH (76.1%), CP (8.1%), CG (0.8%), CC (3.2%), and CCH (46.2%) Vitamins: vitamin C	M´hiri *et al*. (2015)
Potato	Dry peel	Proximal composition: CH (82.3-83.5%) and CP (1.57-1.8%) Amino acids: Ser, Asn, Thr, Glu, Ala, Val, Met, Ile, Lys, His, and Arg Sugars: Fru, Glc, and Sac	Choi *et al*. (2016)
	Dry peel	Proximal composition: CP (13.7%), CG (0.7%), CC (8.1%), CCH (73.4%), and CF (4.2%)	Kleekayai & Suntornsuk (2011)
Rice	Dry peel	Proximal composition: CP (13.2%), CG (18.2%), CC (12.0%), CCH (52.1%), and CF (4.5%)	Schmidt & Furlong (2012)

Moisture content (CH), protein (CP), fat (CG), ash (CC), carbohydrates (CCH), fiber (CF). Fatty acids: lauric (C12:0), myristic (C14:0), palmitic (C16:0), stearic (C18:0), palmitoleic (C16:1), oleic (C18:1), linoleic (C18:2), and linolenic (C18:3). Amino acids: alanine (Ala), arginine (Arg), aspartic acid (Asp), cysteine (Cys), glutamic acid (Glu), glycine (Gly), histidine (His), isoleucine (Ile), leucine (Leu), lysine (Lys), methionine (Met), phenylalanine (Phe), proline (Pro), serine (Ser), threonine (Thr), tyrosine (Tyr), and valine (Val). Minerals: cadmium (Cd), chromium (Cr), selenium (Se), phosphorus (P), potassium (K), calcium (Ca), sodium (Na), magnesium (Mg), copper (Cu), zinc (Zn), manganese (Mn), and iron (Fe). Sugars: glucose (Glc), fructose (Fru), fucose (Fuc), xylose (Xil), mannose (Man), galactose (Gal), arabinose (Ara), rhamnose (Ram), and sucrose (Sac)

In addition, agro-industrial by-products are considered an important source of protein due to their essential amino acid profile, including Cys, Phe, Ile, Leu, Lys, Met, Tyr, Thr, and Val. In addition, they are important source of non-essential amino acids such as Ala, Arg, Asp, Gly, Glu, His, Pro, and Ser (Dadwal *et al*., 2018; Campos-Vega *et al*., 2015; Choi *et al*., 2016). On the other hand, as part of the composition of agro-industrial by-products, different minerals such as Ca, Cu, Fe, Mg, P, K, Na and Zn have been identified (Dreher & Devenport, 2013; Saleem & Saeed, 2020; Scully *et al*., 2016). Another important compound is the fatty acid profile, it has been demonstrated the presence of oleic, linoleic, palmitic, stearic acid, among others (Campos-Vega *et al*., 2015; Dreher & Davenport, 2013). Regarding the carbohydrate profile of the by-products, some works, indicate the presence of Ara, Gal, Glc, Fru, Man, Ram, and Xil (Choi *et al*., 2016; González-Centeno *et al*., 2010; Kruczek *et al*., 2017).

Also, agro-industrial by-products contain several primary vitamins, including vitamin A, vitamin C, vitamin K1, thiamine, riboflavin, niacin, pantothenic acid, vitamin B6, folate, choline, betaine, and vitamin B12 (Dreher & Davenport, 2013; M´hiri *et al*., 2017; Talabi *et al*., 2016). However, some studies have reported the presence of certain anti-nutritional

compounds, some polymers such as pectin and other organic substances such as tannins (Deng *et al*., 2011; Talabi *et al*., 2016). In dried avocado seed, the presence of antinutrients such as alkaloids, tannins, phytic acid, saponins and oxalate has been reported (Talabi *et al*., 2016); while in dried potato peel, the presence of alkaloids, including α-chaconine and α-solanine, was identified (Friedman *et al*., 2017).
In addition, there is recent evidence of some organic acids (nitric and citric, among others) found in agro-industrial by-products; as well as pigments (carotenes) and phenolic compounds (Figure 3), including phenolic acids and flavonoids (Dreher & Davenport, 2013; M´hiri *et al*., 2017; Rosero *et al*., 2019; Scully *et al*., 2016). From the latter group of compounds, gallic, caffeic, and protocatechuic acids have been identified in dried apple seed and pulp (Dadwal *et al*., 2018). In addition, cinnamic and chlorogenic acids were found in dried apple pulp (Dadwal *et al*., 2018; García *et al*., 2009). On the other hand, the presence of caffeic, p-coumaric, ferulic, sinapic, syringic and vanillic acids, as well as flavonoids (+)-catechin, quercetin, apigenin and kaempferol has been reported in avocado seed and fresh peel (Rosero *et al*., 2019). While in dried carrot peel, dried and fresh potato peel, as well as coffee bagasse, some studies report the presence of chlorogenic acid (Friedman *et al*., 2017; Panusa *et al*., 2013; Zhang y Hamauzu, 2004). Other by-products that have been analyzed are grapefruit, lemon and mandarin peels, in which the presence of caffeic, p-coumaric, ferulic and sinapic acids is reported; as well as, the flavonoids hesperidin and naringenin (M´hiri *et al*., 2017). These flavonoids have also been found in dried mandarin and orange seed (Moulehi *et al*., 2012).
Another important source of caffeic and gallic acids is corn cob and the leaves that cover it (Dong *et al*., 2014); however, information on the nutritional value and bioactive compounds of some agro-industrial by-products is still unknown, which could be obtained or recovered for drug development and as feed ingredients, as well as additives for poultry feed.

Compound extraction from agro-industrial by-products

Separation, sterilization and particle reduction processes (flakes/slices or meal), are considered the first steps in the treatment of agro-industrial by-products, and are used to separate impurities, eliminate microorganisms that may alter the composition, as well as increase the recovery of compounds (Azmir *et al*., 2013; Trakulvichean *et al*., 2017). However, it is necessary to use a suitable extraction method to recover any component (Friedman *et al*., 2017; Kruczek *et al*., 2017; Mussatto *et al*., 2011; Saleem & Saeed, 2020).

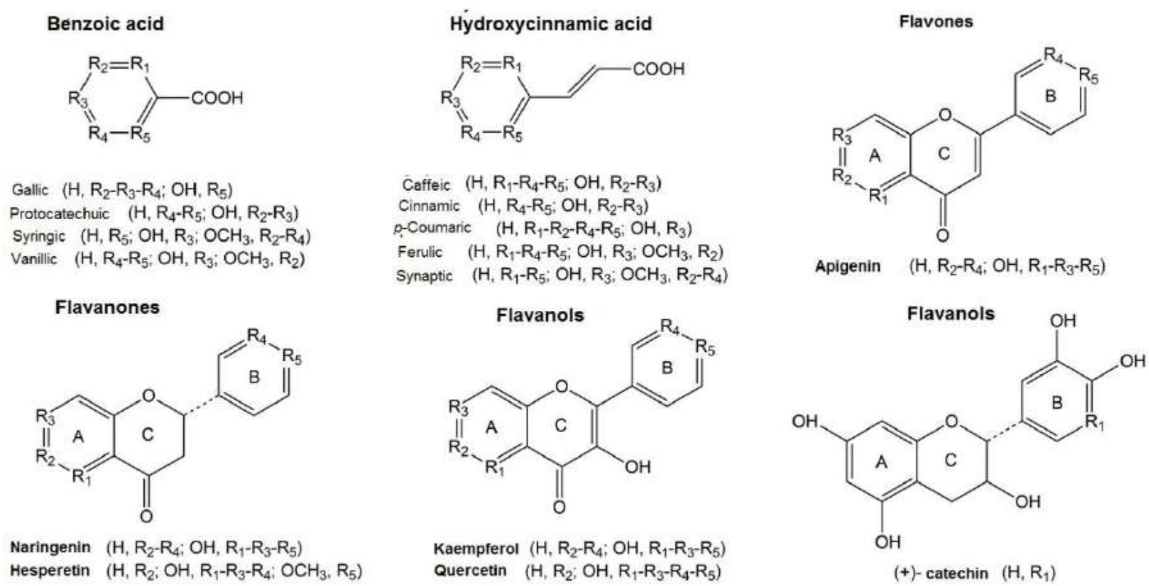

Figure 3. Phenolic compounds present in some agro-industrial by-products

For example, Zhang & Hamauzu (2004), used carrot peel to obtain bioactive compounds. The peel was subjected to a size reduction process, and the compounds were recovered with acetone for 60 minutes (maceration). Subsequently, a separation process (centrifugation) was used to separate the solid from the solvent; while the compounds were concentrated by evaporation of the solvent under vacuum at 35 °C. In another work, García *et al*. (2009) used apple pulp to obtain bioactive compounds, which was previously subjected to a particle size reduction process (grinding and pressing), and subjected to a compound extraction process, using a mixture of acetone and water (7:3) as extraction solvent, and ultrasound-assisted extraction as recovery method. Then solids were separated by centrifugation (17,000xg/10 °C/10 min) and the solvent was evaporated by vacuum at 30 °C, for the recovery of the dry extract. While, Moulehi *et al*. (2012) collected citrus seeds, which were subjected to a process of disinfection, drying and particle size reduction. Subsequently, the bioactive compounds were recovered, using ethanol as extraction solvent for 30 min (maceration). The solvent was filtered and evaporated under vacuum to obtain the dry extract. In addition, Friedman *et al*. (2017) collected different potato species, which were subjected to a disinfection process; as well as separation, drying (lyophilization) and pulverization of the peel. The compounds of the potato peel flour obtained were recovered with a mixture of methanol and water (8:2), using ultrasound as the extraction method (60 min at 60°C). Then, the sample was centrifuged (18,000xg/1°C/10 min) and filtered (0.45 µm), to separate the solid residue, and obtain the liquid extract.

In this context, conventional methods (maceration extraction, Soxhlet and hydrodistillation) and non-conventional methods (enzyme-assisted extraction, microwave, pressurized liquid, supercritical fluids and ultrasound) are commonly used to extract bioactive compounds. However, the combination of these methods with other factors, such as the polarity of the solvent used during extraction, solvent mixtures, solvent-to-solid ratio, solvent pH, solid particle size, temperature, time, and vacuum; as well as fermentation conditions, is necessary (Azmir *et al*., 2013; Chawla *et al*., 2017; Morales *et al*., 2018). Additionally, the use of biotechnological methods such as fungal fermentation in liquid and solid media is considered as an alternative method for the recovery of bioactive compounds from agro-industrial by-products (Vargas-Sánchez *et al*., 2021).

Solid-state fermentation

Solid-state fermentation (SSF) is widely used for the growth or cultivation of fungi, on a solid material or substrate, with low moisture content (Chawla *et al*., 2017; Wang *et al*., 2019). SSF is considered a clean technology for the production or recovery of bioactive compounds from natural sources and their residues; however, the efficiency of this process depends on the fungal species, as well as the environmental conditions and substrate used (Chawla *et al*., 2017; Pleissner *et al*., 2015; Rajavat *et al*., 2020). Regarding environmental conditions, the effect of pH and ingredient composition of the medium, temperature and incubation time, among others, has been demonstrated (Pleissner *et al*., 2015; Xu *et al*., 2019). For example, a previous study indicated that culture medium components (fructose, glycerol, peptone, minerals and vitamins), temperature (22-32 °C) and time (1-11 days) were key factors for the production of solid-state fermented rice polysaccharides (agrosubstrate) with *Cordyceps militaris* (Xu *et al*., 2019).

Regarding the substrate, some research indicates that fungal growth and recovery of bioactive compounds are highly correlated with material composition (water content), physical characteristics of the material (matrix porosity, pore size, particle diameter) and material type (Egbuonu & Osuji, 2016; Shankar & Mulimani, 2007; Saber *et al*., 2010; Torrado *et al*., 2011; Wang *et al*., 2019). In other research, agro-industrial by-products have been used as agrosubstrates for mushroom production; for example, red gram plant by-products, chickpea plant, red chickpea flour, red chickpea husk, wheat bran, rice bran, pineapple, apple and orange residues; as well as peanut cake, sugarcane bagasse, carob pod, corn cob and wheat bran (Shankar & Mulimani, 2007; Torrado *et al*., 2011; Wang *et al*., 2019).

Quail feed additives obtained by SSF

Therefore, it has been demonstrated that SSF could be used to obtain or recover ingredients that can be used in quail feed (Table 2), including proteins and amino acids, fatty acids, antioxidant and antimicrobial compounds, enzymes, vitamins and minerals, from agro-industrial by-products such as agrosubstrates.

These components play an important and specific role in quail performance (feed intake, body weight gain and feed conversion rate), carcass and meat yield, as well as meat quality. Therefore, dietary protein supplementation has been used as a strategy to increase body weight and maintain the characteristic red color of quail breast meat (Cullere *et al*., 2016; Mosaad & Iben, 2009); as well as decrease cooking weight loss and breast toughness (Cullere *et al*., 2016). In addition, the positive effect of dietary supplementation with amino acids on feed intake, weight gain and feed conversion rate of quail subjected to heat stress has been demonstrated (Baylan *et al*., 2006; Del Vesco *et al*., 2014).

The particle size effect (0.18-0.39 mm) and ammonium sulfate concentration on biomass and protein production in solid-state fermented rice bran nutrient solution with *Rhrizopus oryzae* was also determined. The results showed that a reduction in particle size and an increase in ammonium sulfate level increased protein gain. Furthermore, authors concluded that the fermentation process increases the value of the recovered components for potential use in feed formulations (Schmidt & Furlong, 2012). In another investigation, cassava leaves and babassu (*Orbignya* sp.) mesocarp meals fermented in solid state with *Rhizopus oligosporus* were used, these residues were subjected to protein content evaluation. The results showed an increase in protein content and protein digestibility of cassava leaves after the fermentation process, and concluded that SSF from agro-industrial by-products can be used to produce more nutritious foods through the transformation of energy foods into structural foods with more protein (Morales *et al*., 2018).

Table 2. Potential feed additives produced by solid-state fungal fermentation using agro-industrial by-products as agrosubstrates

Additives	Agrosubstrate/Fungus	Relevant results	Reference
Protein/amino acids	Substrate: wheat straw Fungus: *Aspergillus* spp. and *Trichoderma* spp.	(↑) protein content	Rajavat *et al.* (2020)
	Substrate: corn cob Fungus: *Phellinus igniarius*	(↑) protein content	Wang *et al.* (2019)
	Substrate: spent grain - Brewing industry Hongo: *Rhizopus* spp.	(↑) Content of protein and amino acids (↑) content of soluble protein (↑) content of His, Ile, Leu, Lys, Met, Cys, Phe, Tyr, Thr, Val, Arg, Asp, Ser, Glu, Gly, Ala, and Pro	Ibarru *et al.* (2019)
	Substrate: cassava leaves Fungus: *Rhizopus oligosporus*	(↑) protein content and amino acids	Morales *et al.* (2018)
	Substrate: rice bran Fungus: *Rhizopus oryzae*	(↑) protein content	Schmidt & Furlong (2012)
	Substrate: Mango seed Fungus: *Aspergillus niger*, *Penicillium chrysogenum*, *Rhizopus oligosporus*, and *Rhizopus stolonifer*	(↑) Content of Thr, Glu, and Pro content (*A. niger*) (↑) Content of Lys, His, Thr, Glu, Pro, Cys, Ile, Leu, and Tyr (*P. chrysogenum*) (↑)Content of His, Thr, Cys, Ile, and Tyr (*R. oligosporus*) (↑)Content of Lys, His, Arg, Asp, Thr, Ser, Pro, Gly, Cys, Ile, Leu, and Tyr (*R. stolonifer*)	Kayode & Sani (2010)
Fatty acids	Substrate: spent grain - Brewing industry Fungus: *Rhizopus* spp.	(↑) saturated, monounsaturated and polyunsaturated fatty acid content (↑) content of 16:0, 18:0, 18:1n9, 20:0, 20:1n9, 22:0, and 24:0	Ibarru *et al.* (2019)
	Substrate: bakery waste Fungus: *Aspergillus oryzae*	(↑) fatty acid content: myristic, palmitic, palmitoleic, stearic, oleic, arachidonic, linoleic, and linolenic acids	Pleissner *et al.* (2015)
Antioxidants and antibacterials	Substrate: rice Fungus: *Cordypces militaris*	(↑) Polysaccharide content. (↑) Inhibition of the DPPH radical	Xu *et al.* (2019)
	Substrate: potato skin Fungus: *Morchella* spp.	(↑) Polysaccharides - chitin content	Papadaki *et al.* (2019)
	Substrate: corn cob Fungus: *Phellinus igniarius*	(↑) Flavonoid content	Wang *et al.* (2019)
	Substrate: spent grain – brewing industry Fungus: *Rhizopus* spp.	(↑) phenol content. (↑) DPPH radical inhibition	Ibarru *et al.* (2019)
	Substrate: grape pomace Fungus: *Aspergillus niger*	(↑) phenols, anthocyanidins and proanthocyanidins content. (↑) ABTS radical inhibition.	Teles *et al.* (2018)
	Substrate: Rice bran Fungus: *Rhizhopus oryzae*	(↑) phenolic acids: gallic, protocatechuic, chlorogenic, *p*-hydroxybenzoic, caffeic, syringic, vanillin, *p*-coumaric, and ferulic. (↑) Inhibition of DPPH radical, peroxidase and polyphenol oxidase enzymes.	Schmidt *et al.* (2014)
	Substrate: pomegranate peel Fungus: *Aspergillus niger*	(↑) phenol content, DPPH radical inhibition, and protection against *β*-carotene oxidation. (↓) total account of *Staphylococcus aureus*, *Escherichia coli*, *Klebsiella pneumonia*, and *Pseudomona aeruginosa*	Bind *et al.* (2014)
	Substrate: rice bran Fungus: *Rhizopus oryzae*	(↑) phenol content	Schmidt & Furlong (2012)

	Substrate: potato skin Fungus: *Rhizopus oryzae*	(↑) polysaccharides - chitosan content	Kleekayai & Suntornsuk (2011)
	Substrate: blueberry pulp Fungus: *Lentinus edodes*	(↑) phenol content (↓) total account of *Listeria monocytogenes*, *Vibrio parahaemolyticus*, and *Escherichia coli*	Vattem *et al.* (2004)
Enzymes	Substrate: wheat straw Fungus: *Aspergillus* spp. and *Trichoderma* spp.	(↑) endoglucanase, exoglucanase, xylanase, and cellobiase contents	Rajavat *et al.* (2020)
	Substrate: pistachio shell Fungus: *Lentinus tigrinus*	(↑) laccase content	Sadeghian-Abadi *et al.* (2019)
	Substrate: onion juice Fungus: *Pleurotus sajor-caju*	(↑) pectinase content	Pereira *et al.* (2017)
	Substrate: potato waste Fungus: *Aspergillus ficuum*	(↑) phytase content	Tian & Yuan (2016)
	Substrate: vinegar processing Waste Fungus: *Aspergillus ficuum*	(↑) phytase content	Wang *et al.* (2011)
	Substrate: rice bran, wheat and black gram, coconut oil and peanut oil waste Fungus: *Aspergillus niger*	(↑) *α*-amylase content	Suganthi *et al.* (2011)
	Substrate: wheat bran, orange and sugarcane Fungus: *Thermomucor indicaeseudaticae*	(↑) pectinase content (	Martin *et al.* (2010)
	Substrate: rice seed waste Fungus: *Aspergillus niger*	(↑) *β*-glucanase and xylanase content	Wang & Feng (2009)
	Substrate: Chickpea, wheat and rice bran, pineapple, apple, orange, peanut, sugarcane and carob residues Fungus: *Aspergillus oryzae*	(↑) *α*-galactosidase content	Shankar & Mulimani (2007)
	Substrate: Babassu oil waste Fungus: *Penicillium restrictum*	(↑) lipase, protease and amylase content	Palma *et al.* (2000)
Acidifiers	Substrate: orange peel Fungus: *Aspergillus niger*	(↑) citric acid content	Torrado *et al.* (2011)
	Substrate: rice straw stems Fungus: *Alternaria* spp., *Aspergillus* spp., *Penicillum* spp., and *Stachybotrys* spp.	(↑) content of acetic, citric, formic, malic, succinic, and oxalic acids	Saber *et al.* (2010)
	Substrate: sugarcane pulp Fungus: *Rhizopus oryzae*	(↑) lactic acid content.	Soccol *et al.* (1994)
Vitamins	Substrate: rice straw stems Fungus: *Alternaria* spp., *Aspergillus* spp., *Penicillum* spp., and *Stachybotrys* spp.	(↑) vitamin C content.	Saber *et al.* (2010)
	Substrate: spu paste Fungus: *Lentinus edodes*	(↑) vitamin D content.	Choi *et al.* (2005)
Minerals	Substrate: black-eyed pea Fungus: *Aspergillus oryzae*	(↑)) iron and zinc content	Chawla *et al.* (2017)

(↑), increase relative to control; (↓), decrease relative to control

On the other hand, it has been shown that dietary supplementation with medium-chain fatty acids increased the immune response and reduced total cholesterol and triglycerides in birds; as well as the abdominal fat content of quail breasts (Saeidi *et al*., 2016). Consequently, these feeding conditions can improve the oxidative stability of quail meat and increase meat quality during storage (Ghazaghi *et al*., 2014).

Natural sources of antioxidant and antimicrobial compounds have been used to increase feed intake, weight gain, carcass yield of quail, decrease harmful microbial populations in the gut, and reduce lipid oxidation in quail breast and thigh meat (Ghazaghi *et al*., 2014; Ghasemi-Sadabadi *et al*., 2020). In this context, Bind *et al*. (2014), in a previous work, antioxidant and antimicrobial phenolic compounds of solid-state fermented pomegranate peels with *Aspergillus niger* were evaluated. The results showed increased phenolic compounds, antioxidant activity against DPPH free radical and antibacterial properties against *Klebsiella pneumoniae*. They also concluded that SSF of agro-industrial by-products is a potential strategy to obtain antioxidant and antibacterial compounds (Bind *et al*., 2014).

Additionally, enzymes (phytase, ɑ-galactosidase, β-glucosidase, β-glucanase, endo- and exocellulase, lipase, proteases and xylanase) have been employed as poultry feed additives which are characterized by possessing different functions. For example, phytase breaks down non-digestible phytic acid (phytate) and releases phosphorus, calcium and other digestible nutrients (Shehab *et al*., 2012); while *α*-galactosidase releases polysaccharides from botanical sources improving their digestion and absorption (Munir & Maqsood, 2013). In addition, *β*-glucosidase, *β*-glucanase and endo- and exocellulase enzymes degrade the cell wall structure of botanical sources and enhance nutrient digestion and absorption (Kilany & Mahmoud, 2014; Munir & Maqsood, 2013). Also these enzymes reduce intestinal tract viscosity, remove anti-nutritional factor, increase immunity and improve quail performance (Chawla *et al*., 2017; Kilany & Mahmoud, 2014).

Other enzymes such as xylanase are characterized by breaking down xylan from botanical material, and the xylan-oligosaccharide breakdown product formed can improve the flora and immune response of beneficial intestinal microorganisms (Munir & Maqsood, 2013). While lipases and proteases are commonly used to stimulate the excretion of endogenous digestive enzymes, improving energy efficiency, taste, digestion and absorption of lipids and proteins, respectively (Munir & Maqsood, 2013; Mnisi & Mlambo, 2018). In a previous work, phytase production from potato waste was evaluated by SSF with *Aspergillum ficuum*. The results of this work showed an increase in phytase production after the fermentation process; indicating that pH, inoculum level and moisture content did not affect phytase production. Therefore, they concluded that SSF could be used to take advantage of food waste and produce value-added products (Tian & Yuan, 2016).

In poultry production, inadequate feeding of birds is one of the most common problems leading to vitamin and mineral deficiencies, which increases health problems and

mortality. Therefore, dietary supplementation of vitamins and minerals in quail diets is a common and routine practice (Imik *et al*., 2010; Sahin *et al*., 2005). In this regard, dietary supplementation with vitamin E and C decreased lipid oxidation, total aerobic and coliform counts in quail breast meat, and improved the red color of samples (Imik *et al*., 2010). Dietary supplementation with minerals improves performance and antioxidant status of heat-affected quail (Sahin *et al*., 2005). In addition, dietary supplementation with organic acids has been considered as a strategy to avoid antibiotic use and increase feed intake and weight gain of quail (Khan *et al*., 2016). Thus, in a previous study, vitamin D production in soybean paste by SSF with *Lentinus edodes* and *Pleurotus eryngii* was investigated. The fermentation process increased the vitamin D2 content; in addition, SSF increased the nutritional fortification of the plant materials (Choi *et al*., 2005).
Another study determined SSF effect with *A. oryzae* on the mineral content of *Vigna unguiculata* seed meal, revealing an increase in mineral components (iron and zinc) after the fermentation process. Authors concluded that SSF improved mineral bioavailability (Chawla *et al*., 2017).

CONCLUSION

Solid-state fungal fermentation using agro-industrial by-products as agrosubstrates may be a promising strategy for obtaining quail feed additives, including proteins and amino acids, fatty acids, antioxidant and antibacterial compounds, enzymes, acidifiers, vitamins and minerals.

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Errata Erratum

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