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Review

Potential health benefits of natural products derived from truffles: A review

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A B S T R A C T

Background: Truffle, the hypogeous, ascomycetous macrofungus, has been an appreciated food for ages, and it is gaining elevated status in the culinary domain. With the identification of its components such as ergosterol, tuberoside anandamide, polysaccharides, and phenolics, as well as the validation of nutritional benefits as antioxidant, anti-inflammatory, immunomodulatory, antitumor, antimicrobial, and aphrodisiac, it is attracting international consumer attention. However, due to the huge chasm between demand and supply, some varieties, such as the white *Tuber magnatum* and the Périgord or black truffle *Tuber melanosporum* are very expensive, which restricts their accessibility to only a limited population.
Scope and approach: This review summarizes the relevant literature and available data pertaining to the nutritional, health, and medicinal benefits and uses of truffles. So, this review can be a good reference for truffle research.
Key findings and conclusions: Truffle plantations are being established, but they are riddled with a variety of challenges. The biological roles are also scantily-evaluated, unlike mushrooms, which render some potential consumers skeptic regarding their food safety. Awareness of their present standing might kindle interest among researchers to investigate their food and health scopes and to design strategies to enhance productivity.

1. Introduction

Nutritious food is a need of the time, as a balanced, minimally-processed diet can avert a number of inflammatory diseases (Anand et al., 2015; Myles, 2014). In this regard, truffles, the edible hypogeous (10–30 cm below ground) and ascomycetous fungi appear promising (Mello, Murat, & Bonfante, 2006). Their nutritional and gustatory value is already of immense repute. They are highly regarded in the gourmet culinary world (*haute cuisine*), evident from the sobriquets 'underground gold' and 'diamond of the kitchen' (Tang, Liu, & Li, 2015). However, their consumer base is meager. It is their low productivity that makes them expensive and inaccessible to the majority of the world's population. Global production of truffles is hundreds of tonnes, which is insufficient. Due to the stark mismatch between supply and demand, the cost can surge to US $5000 per kilogram of white truffles (other types can be much cheaper, especially desert truffles). Given the exorbitant price, only epicurean restaurants serve them and only the rich can afford this delicacy. If the global truffles yield can be improved, their cost will drop and more people can avail their benefits. Integrative approaches, including artificial inoculation and fermentation, can materialize this objective. To contribute in this regard, this updated review has been compiled. Accordingly, the aim of the present review is to summarize the current status of knowledge on truffles, their bioactive compounds, and their medicinal uses in the treatment of different illnesses.

2. Truffle biology, morphology, and distribution

Truffles grow as symbiotic ectomycorrhizae (ECM) on the roots of a wide variety of plants, both gymnosperms and angiosperms of

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temperate, boreal, and sub-tropical forests (Mello et al., 2006; R.; Splivallo, Fischer, Gobel, Feussner, & Karlovsky, 2009). These fungi release the auxin class hormone indole-3-acetic acid (IAA) and ethylene, which influence roots of the host plants (Fu et al., 2015; Splivallo et al., 2009). It is generally assumed that truffle species distribution is favoured by warm and fairly dry climates, and calcareous soils, depending on the type of truffle; as an example, *Tuber melanosporum* grows naturally in the calcareous soils of Spain, France, and Italy, (Linde & Selmes, 2012; Martin et al., 2010).

A hundred different kinds of truffles have been discovered around the world, and new species are being discovered regularly. These fungi grow in almost all continents, however, most of the edible varieties have been identified in various parts of Europe (particularly in France, Italy, England, Spain, and Croatia), Australia, New Zealand, North America (Pacific North West and British Columbia) (Berch & Bonito, 2016), Asia (China and Middle East), and Africa (Ferdman, Aviram, Roth-Bejerano, Trappe, & Kagan-Zur, 2005), among others. These truffles generally belong to the genus *Tuber* (Bonito et al., 2013). Desert truffles grow seasonally in several areas such as Bahrain, Jordan, Syria, Iraq, Oman, Kuwait, Saudi Arabia, Morocco, Libya, Egypt, Algeria, South Africa, Botswana, and Tunisia (El Enshasy, Elsayed, Aziz, & Wadaan, 2013; Mandeel & Al-Laith, 2007). They sprout in the deserts after rain (Bradai, Neffar, Amrani, Bissati, & Chenchouni, 2015). Desert truffles mostly include *Terfezia* and *Tirmania* genus (El Enshasy et al., 2013). They are locally known as kamma, kemeh, terfass, fagga, or zubaydi in the Middle Eastern region. Most culinary-grade truffles belong to family Tuberaceae, Pezizaceae and Terfeziaceae (Bonito et al., 2013; El Enshasy et al., 2013). Truffles have a large genome size, as observed in the *T. melanosporum* (black truffle) model, that has a genome size of 125 Mb (Chen et al., 2014). Their transposable element (TE) and repetitive DNA content comprised more than > 58% of the genome (Chen et al., 2014).

Truffles vary in their texture (wrinkled, bruised, smooth, and reticulate) and color (white, brown, and black). Shapes are generally lobed potato-like, which justifies their popular generic name *Tuber*. White truffles include *Tuber magnatum*, *T. maculatum*, *T. borchii*, *T. dryophilum*, *T. puberulum, T. oregonense* (Oregon white truffle), and *T. latisporum*, whereas black truffles include *T. brumale*, *T. melanosporum* (Perigord Truffle), *T. aestivum* (summer truffle), *T. uncinatum* or *T. aestivum* (Burgundy truffle), *T. indicum*, and *T. himalayense* (Zhang, Yang, & Song, 2005). The white truffle *T. magnatum*, found mostly in Italy and some East European countries such as Croatia, Hungary, and Romania, is the most-hunted and prized truffle species (Gioacchini et al., 2008; Roux et al., 1999; Zampieri, Murat, Cagnasso, Bonfante, & Mello, 2010). On the other hand, black truffle *T. melanosporum*, also called the 'black diamond of cuisine', is mostly harvested in France, Italy, and Spain (Liu et al., 2015). Evolutionary analyses have showed that white and black truffles are not monophyletic lineages (Chen & Liu, 2007). Furthermore, the historical, cultural, and socio-economic significance of truffles has been reviewed (Patel, 2012). Accordingly, and owing to the wide range of nutritional, preventive, and therapeutic profile of truffles against a wide range of illnesses, this review focuses on the nutritional benefits, chemo-preventive and therapeutic ability of truffles. In addition, the review touches upon the bioactive compounds present in truffles.

3. Nutritional profile and characterization of bioactive components

Truffles are rich in protein, fat, dietary fibre, ash, essential amino acids (methionine, phenylalanine, valine, serine, isoleucine and threonine), and metals (K, P, Fe, Cu, Zn and Mn). For example, chemical analysis of desert truffles showed that protein constitutes 20–27% of the dry matter (El Enshasy et al., 2013). In addition, truffles contain volatile organic compounds (VOCs) such as aldehydes, alcohols, ketones, and organic acids (ascorbic acid) in various ratios (Federico et al., 2015). Recent studies have proven that some truffles have ergosteroids, the most widespread fungal sterol, that can be transformed into vitamin D in the human body (Doğan & Aydın, 2013). Ergosterol (ergosta-5,7,22-trienol) and brassicasterol (ergosta-5,22-dienol) have been identified as key components of *T. melanosporum*, (Harki, Klaebe, Talou, & Dargent, 1996), whereas tuberoside, a steroidal glucoside with a polyhydroxyergosterol nucleus, has been found in *T. indicum* (Jinming, Lin, & Jikai, 2001). These steroidal glucosides might have pharmaceutical relevance (Jinming et al., 2001).

Truffles are cherished food commodities for their unique aromatic compounds, which connoisseurs depict as seductive and unique (Pacioni, Cerretani, Procida, & Cichelli, 2014; Splivallo, Ottonello, Mello, & Karlovsky, 2011). Headspace solid-phase extraction followed by GC–MS (gas chromatography–mass spectrometry) analysis enabled the identification of contributing aromatic compounds. A sulfur-containing compound, 3-methyl-4,5-dihydrothiophene, was detected in *T. borchii*, and thiophene derivatives are major contributors to the human-sensed aroma of this fungus (Splivallo & Ebeler, 2015). Thiophene-core compounds possess estrogen receptor manipulating ability (Min et al., 2013).

A recent study characterized the bacterial community of the white truffle *T. borchii*, and found them to be dominated by α- and β-proteobacteria. Results from this study found that the sulfur-containing volatiles such as thiophene derivatives, characteristic of *T. borchii* fruiting bodies, originate from the transformation of non-volatile precursors of truffles into volatile compounds via these bacteria (Splivallo et al., 2015). In addition, bacteroides, actinobacteria, and firmicutes were the predominant bacterial members of the truffle microbiome (Benucci & Bonito, 2016), whereas a nitrogen-fixing bacterium *Bradyrhizobium* is associated with *Tuber* ascocarps (Christine Le Roux et al., 2016).

Aroma of truffles can range from mild to intense, and can vary from cheese-like, earthy, garlicky, pungent, vanilla-like, creamy, leathery, dusty, to gasoline like (Xiao et al., 2015). It is believed that the complex aroma profile of truffles has been attributed to the climate and soil they are grown in, just like that of grapes and wheat (Wang, Sun, & Chang, 2015). Also, the microbiome on truffles are regarded responsible for the aroma profile (Vahdatzadeh, Deveau, & Splivallo, 2015). More than 200 microbial volatile organic compounds (VOCs) have been reported from truffles, the abundance of which has been explained as the role of these signals in communication and regulation of their life cycles (Kanchiswamy, Malnoy, & Maffei, 2015). In this context, the aldehyde 2-octenal is common to both white as well as black truffles (Kanchiswamy et al., 2015), whereas bis(methylthio) methane has been identified as a major aroma component of the white truffle *T. magnatum* (Kanchiswamy et al., 2015). Aroma compounds detected in the black truffle *T. melanosporum* are 2,3-butanedione (Diacetyl), dimethyl disulphide (DMDS), ethyl butyrate, dimethyl sulphide (DMS), 3-methyl-1-butanol, and 3-ethyl-5-methylphenol (Liu et al., 2013).

Terpenoids such as carveol, *p*-cymene, cumene hydroperoxide, guaiene, and limonene have also been detected in a number of truffles (Kanchiswamy et al., 2015). Furthermore, a musk odour signalling pheromone 5-androstenol (5alpha-androst-16-en-3alpha-ol), belonging to the 16-androstenes group, has also been detected in truffles (Wang, Li, Li, & Tang, 2008). A recent study on *T. melanospermum* has showed that truffles contain anandamide and several prominent metabolic enzymes of the endocannabinoid system (Pacioni et al., 2015). Anandamide (*N*-arachidonoylethanolamine) is a fatty acid neurotransmitter derived from