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Review

A comprehensive review on the health benefits, phytochemicals, and enzymatic constituents for potential therapeutic and industrial applications of Turkey tail mushrooms

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Received: 23 September 2023 / Accepted: 2 May 2024
Published online: 09 May 2024

Abstract

This comprehensive literature review delves into the multifaceted attributes of *Trametes versicolor*, commonly known as turkey tail mushroom. The turkey tail mushroom stands as a noteworthy source of diverse bioactive compounds with potent health benefits. This review offers a contemporary synthesis of its phytochemical constituents and their multifaceted impacts on human health. The mushroom's intricate composition, encompassing polysaccharides, phenols, and triterpenes, underpins its remarkable therapeutic potential. Focusing on key attributes such as anti-cancer, antimicrobial, and immunomodulatory activities, this review delves into the intricate mechanisms by which the turkey tail mushroom exerts its effects. In addition, the exploration extends to the enzymatic constituents inherent in the mushroom and their industrial significance. Mechanisms of action for both phytochemicals and enzymes are studied, providing a well-rounded understanding of their roles in conferring therapeutic and industrial benefits. This synthesis of research aims to provide an up-to-date perspective on turkey tail mushrooms' versatile applications. By intertwining the exploration of health benefits and enzymatic constituents, this review offers insights into the potential of harnessing this natural resource for innovative therapeutic strategies and industrial applications. Overall, it contributes to the advancement of knowledge and utilisation of turkey tail mushrooms' diverse properties for human health and industrial progress.

Article highlights

- In-depth analysis of turkey tail mushroom's bioactive compounds and their physiological significance.
- Exploring the mushroom's enzymatic composition and their applications.
- Detailing the mushroom's potential in combating diseases by unveiling their mechanistic actions.

Keywords Turkey tail · *Trametes versicolor* · Health benefits · Enzymes · Phytochemicals · Polysaccharides

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1 Introduction

The global medicinal mushroom market is increasing exponentially. In 2022, the market size was valued at USD 10.9 billion and is now forecasted to grow from USD 11.6 billion in 2023 to $19.1 billion by 2032. The turkey tail mushroom is one of the medicinal mushrooms that dominates the medicinal mushroom market together with shiitake, maitake, reishi, chaga and cordyceps amongst others [1]. In the realm of natural resources with untapped therapeutic potential, *T. versicolor*, commonly known as turkey tail mushroom, has emerged as a subject of growing interest. With an intricate fusion of ancient traditions and modern scientific advancements, this review delves into the multifaceted attributes of turkey tail mushrooms, shedding light on its intricate mechanisms, diverse bioactive compounds, and promising applications.

Throughout history, traditional medicine systems have revered the turkey tail mushroom for its health-enhancing properties. Recent scientific inquiry has validated its esteemed status by unveiling the mechanisms underlying its potential to combat cancer, ward off pathogens, and modulate immune responses [2, 3]. Beyond its role in human health, this review also delves into the mushroom's enzymatic constituents, exploring their significance in industrial contexts.

The rich phytochemical composition of turkey tail mushrooms, encompassing polysaccharides, phenols, triterpenes, and more, serves as the foundation for its diverse effects. With anti-cancer, anti-microbial, and immunomodulatory activities at the forefront, these bioactive compounds resonate with contemporary healthcare needs [4, 5]. The exploration doesn't halt at phytochemicals; enzymatic components embedded within the mushroom offer an intriguing avenue for industrial applications, promising advances in biotechnology and manufacturing [6, 7].

Thus, as the boundaries between traditional wisdom and scientific rigour blur, this review endeavours to provide a comprehensive and updated review of turkey tail mushrooms' various applications, bridging the gap between the past and the future.

2 Methodology

2.1 Literature search strategy

A comprehensive literature search was conducted to identify relevant studies pertaining to the health benefits, phytochemical composition, and enzymatic constituents of turkey tail mushrooms. Databases including PubMed, Scopus, Web of Science, and Google Scholar were used to search for articles. The search terms used included variations of "*Trametes versicolor*," "the phytochemicals of *T. versicolor*," "health benefits of *T. versicolor*," "anticancer activity of *T. versicolor* " "antimicrobial activity of *T. versicolor*," "enzymes in *T. versicolor*" "physiological mechanisms of the enzymes in *T. versicolor* and their applications," "immunomodulatory properties of *T. versicolor*," "antioxidant activity of *T. versicolor*," and "physiological mechanisms of *T. versicolor*."

2.2 Inclusion and exclusion criteria

Articles were selected based on their relevance to the objectives of the review. Furthermore, articles were included if they provided substantial information on the phytochemical constituents of turkey tail mushrooms and their associated health benefits. Studies focusing on mechanisms of anti-cancer, cardioprotective, immunomodulatory, anti-oxidant, anti-microbial, and immunomodulatory activities were prioritized. Additionally, articles providing substantial research on turkey tail's enzymatic constituents and industrial applications were also included. Reviews and original research articles were considered for inclusion. Non-English articles and studies without full-text availability were excluded. Articles containing irrelevant or insubstantial data were excluded.

3 The biology of turkey tail mushrooms

Turkey tail mushrooms (*T.versicolor*; Synn. *Coriolus versicolor*), a species of bracket fungus from boreal woodlands belong to the Polyporaceae family [8]. These mushrooms are typically found in temperate climates and prefer humid surroundings. As seen in Fig. 1, they are so named because of their bright and intricately patterned crowns, which resemble the feathers of wild turkeys. The thin, fan-shaped caps (2–10 cm in diameter) are covered in concentric rings that range in colour from varying hues of brown, orange, and blue to green, pink, and purple. The intricate patterns on the cap are created

by concentric rings of varying colors, that are formed in the process while the mushroom grows providing them their distinctive turkey tail-like appearance. The underneath of the cap possesses many tiny pores that help release the spores.

Turkey tail mushrooms being saprotrophic in nature depend on dead or decaying plant debris, such as logs, stumps, and even living trees as the source of their nourishment [9]. They have a peculiar capability in breaking down lignin, a complex polymer found in the cell walls of wood, which makes them an important component of the ecosystem's nutrient cycling process.

These mushrooms are a good source of food for a variety of animals, including insects, slugs, and snails. They also host several parasitic fungi and bacteria, which can infect the mushroom and cause it to change colour or shape.

Furthermore, these mushrooms are used for their possible environmental benefits in addition to their potential medicinal value. These fungi are being investigated for their potential to degrade hazardous contaminants in soil and water and to create hydrogen, which may be used to provide renewable energy. Therefore, these mushrooms are an intriguing and adaptable species with a variety of biological and therapeutic uses and are one of the highly investigated medicinal mushrooms [8]. They are an intriguing topic for research for both scientists and naturalists due to their exquisite patterns, distinctive ecology, and potential for application in biotechnology.

4 The therapeutic importance of Turkey tail mushrooms

As shown in Fig. 2, a salient feature associated with turkey tail mushrooms is their therapeutic potential [10, 11]. These mushrooms have been used for medicinal purposes in traditional Chinese, Japanese, and Native American medicine for centuries [8]. They have historically been made as tea or soup to cure several illnesses, such as the flu, the common cold, and stomach issues. Although these mushrooms are typically dried and brewed as tea or added to soups and stews, they can also be consumed in capsule form as a dietary supplement. It is important to note that while turkey tail mushrooms are generally considered safe, they may interact with certain medications and should be avoided by individuals with autoimmune disorders or allergies to mushrooms. Recently, turkey tail mushrooms have attracted a lot of interest due to their conceivable anti-cancer qualities, possibly as a result of their capacity to activate the immune system's attachment to cancer cells. According to certain research, these mushrooms might be used to treat cancers, such as breast, lung, and colorectal cancer [12]. Additionally, these mushrooms are used by patients for a variety of diseases, including muscle strength, weariness, urinary tract infections (UTIs), and disorders that affect radiation and cancer treatments. However, these must be supported by empirical research.

As seen in Fig. 3, available literature suggests that these fungi possess several biologically active compounds, including polysaccharides (β-glucans) [13, 14], ergothioneine, krestin, sterols (such as ergosterol), terpenoids, and phenolic compounds, that possess immunomodulatory, anti-bacterial, anti-inflammatory, and antioxidant effects [15–17]. It

Fig. 1 A depiction of the T.versicolor (Image generated with AI software)

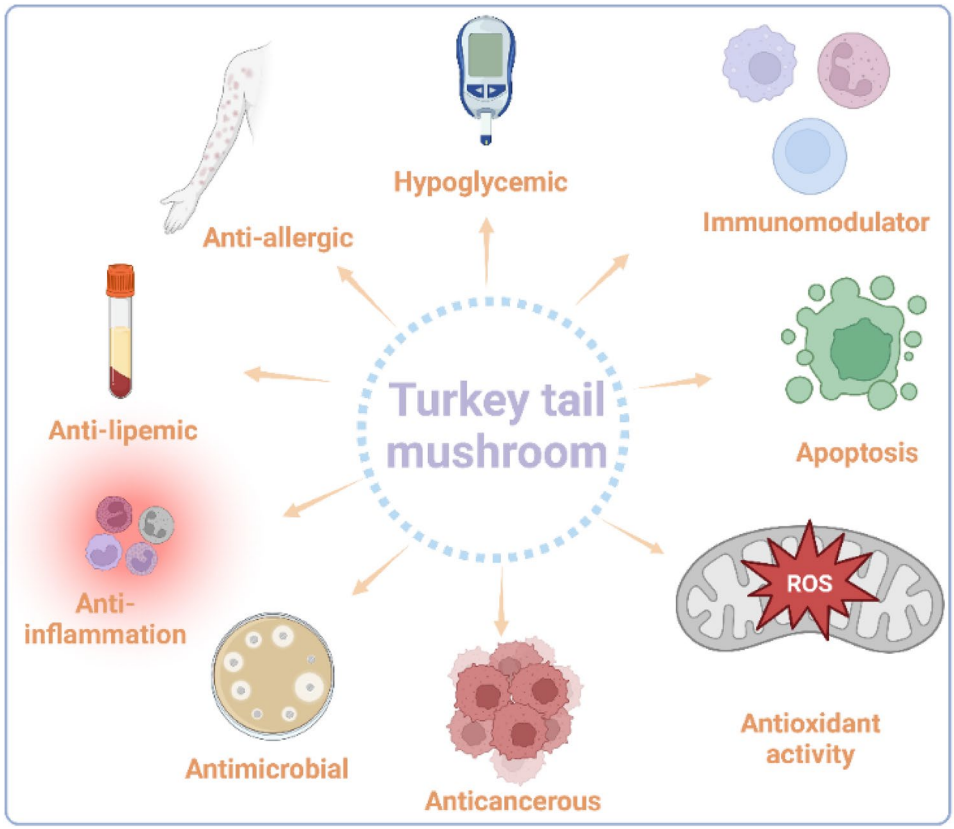

Fig. 2 Utilization of the extracts of Turkey tail mushrooms for curing different ailments. As seen in the image below extracts obtained from turkey tail mushrooms can be applied to treat various diseases ranging from allergies to inflammation and bacterial infections

also has a pigment called melanin that has antioxidant, radioprotective, and immunostimulatory properties [8, 18, 19]. Moreover, ergothioneine has neuroprotective properties. Numerous studies have been conducted on these substances and their possible therapeutic uses, which makes them interesting to scientists looking into the therapeutic benefits of turkey tail mushrooms.

4.1 Immunomodulating properties

T. versicolor contains antioxidants, polyphenols, terpenes and other compounds. It enhances the innate and adaptive immune response [5], support the treatment of cancer diseases, and maintain healthy gut bacteria. Many clinical researches suggest that, *T. versicolor* plays a great roll as antitumor activity against many cancer diseases [20, 21] particularly breast cancer [22, 23], lung cancer [24], gastric cancer [24], and colorectal cancer [25]. This effect may be related to its underlying immunologic activity. It was reported by many researchers that different extracts and fractions of *T. versicolor* have potent immune-modulating activities [26]. *T. versicolor* components enhance the cluster of differentiation 69 (CD69) activation marker on monocytes and lymphocytes. Activation of the cell surface marker CD69 will be upregulated on many immune cell types, that result in activation of natural killer (NK) cells CD69 expression and NK cell-mediated tumour-killing activity [27].

Other studies found that the *T. versicolor* also contains protein-bound polysaccharides like polysaccharide krestin (PSK) and polysaccharide peptides (PSP) [28]. These polysaccharide-peptides play a role in promoting the immune response by activating and inhibiting specific immune cells and also by reducing inflammation. It was reported that the PSP enhance the activation of monocytes to boost immunity and fight infection by phagocytosis and the release of cytokines [29]. Furthermore, PSK stimulates other types of cells called dendritic cells which act as antigen-presenting cells and regulate the immune response, and also, activate the natural killer cells which attack tumours [20]. Thus, dendritic cells stimulated by PSK help to regulate immune response and toxin immunity. Additionally, PSK promotes monocyte and macrophage production.

One must note, that these PSP and PSK are included in the group of biological response modifier. It means that they can restore the balance to the immune system without a specific target [30]. Another perspective is that these

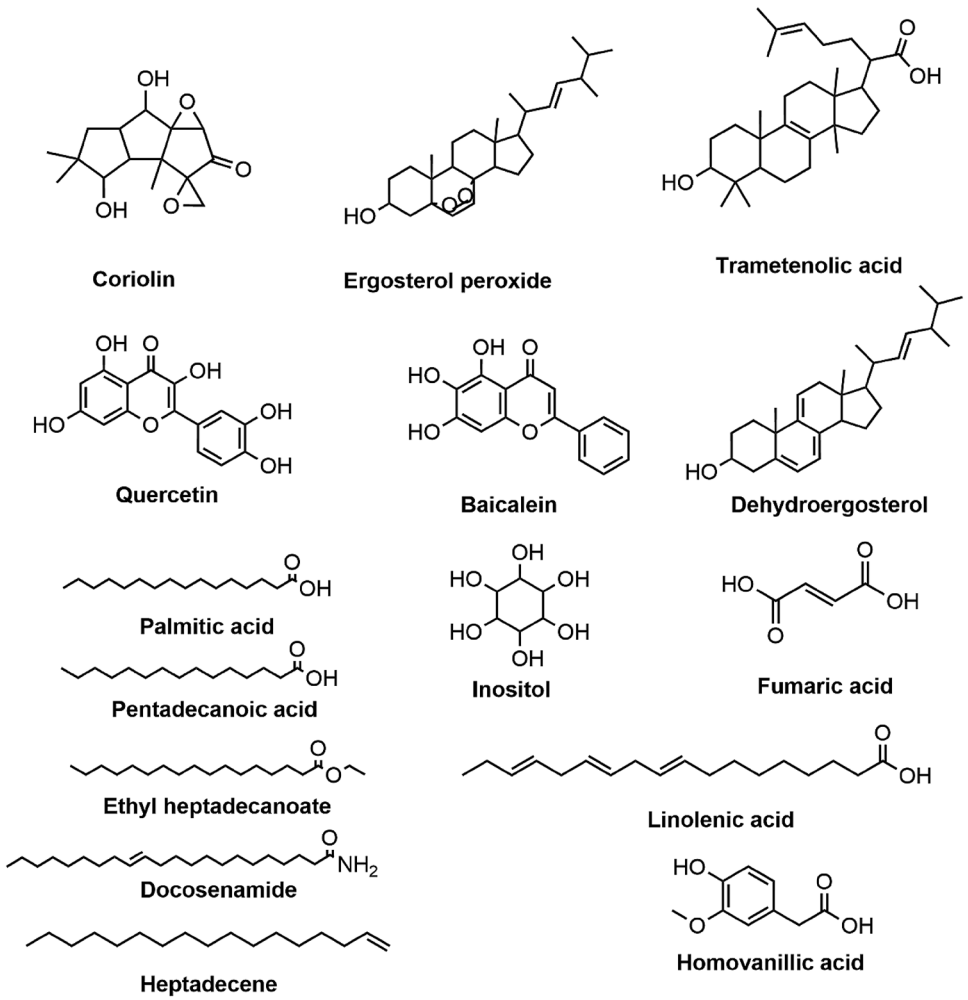

Fig. 3 Some prominent bioactive compounds found in the mycelium and the fruiting bodies of turkey tail mushrooms. The phytochemcial composition of turkey tail mushrooms is a vast one and some of the prominent ones can be appreciated in the figure below. Naturally, each bioactive compound is vital in contributing to the medicinal benefits of this mushroom

polysaccharide-peptides are differed from one strain to another depending on the strain of *T. versicolor*, growing conditions, and extraction process [31].

Moreover, turkey tail mushrooms exhibit immunological effects through their fruiting bodies and mycelial extracts [32, 33]. These effects are attributed to interactions between the mushroom cell wall components, particularly protein-bound polysaccharides, and Langerhans cells in the oral cavity. Additionally, complex interactions occur with dendritic cells, which subsequently impact various immune cells in normal mice. Moreover, the stimulation of T cells, B lymphocytes, monocytes, macrophages, and bone marrow cells is likely to occur when exposed to these mushrooms [32, 34–36]. According to preclinical studies [37], polysaccharides content in the *T. versicolor* extracts can act as mitogen by inducing the proliferation of both T and B lymphocytes.

4.2 Anti-microbial properties

Antibacterial activity studies have shown that turkey tail methanolic extracts have bactericidal activity against both Gram-positive and Gram-negative bacteria [38]. Other studies on *T.versicolor* components or extracts have shown that can inhibit the growth of *S. aureus* [18], *Fusarium langsethiae* (exo-proteome of *T. versicolor*) [39], methicillin-resistant *Staphylococcus aureus* [40] and *Saccharomyces cerevisiae* [41]. Additionally, turkey tail mushroom extracts exhibit broad-spectrum antibacterial and antifungal capabilities against well-known pathogens like *Escherichia coli*, *Pseudomonas aeruginosa*, *Candida albicans*, *Klebsiella pneumoniae*, *Listeria monocytogenes*, and *Streptococcus pneumoniae*. Activation of polymorphonuclear cells and enhanced release of antimicrobial cytokines such as tumour necrosis factor and interleukin (IL)-1 are most likely to responsible for these antimicrobial effects. Turkey tail extracts also have antiviral properties.

Notably, the leishmaniasis-causing parasite *Leishmania amazonensis* has shown action against the promastigotes and amastigotes of lanostane isolated from turkey tail.

Furthermore, PSK demonstrates broad antiviral effects, inhibiting HIV reverse transcriptase, lymphocyte binding, and cell-to-cell infection of human immunodeficiency virus type 1 (HIV-1), HIV-2, and human T-lymphocytic virus type 1 (HTLV-1) [42]. Additionally, it inhibits herpes simplex virus (HSV)-1 and HSV-2, improves host defenses against bacterial and fungal infections, stimulates the generation of interferon (IFN), and encourages NK cell activity against cytomegalovirus [43]. Additionally, PSK improves antibacterial efficacy and boosts antibiotic sensitivity while exhibiting protective qualities against fatal *Candida albicans* infection [44, 45]. PSK suppresses B-cell development in Epstein-Barr virus-infected lymphocytes, stimulates T and NK cells, and increases cytotoxicity against infected B cells [44].

With regards to the in-vitro activity of PSP which is isolated from *T. Versicolor* against HIV-1 it inhibits the interaction between HIV-1 gp120 and the CD4 receptor (IC_{50} = 150 µg/ml). In addition, it inhibited recombinant HIV-1 reverse transcriptase at a concentration of 62.5 nM (IC_{50} = 6.25 µg/ml) [46]. The efficacy of PSP was also demonstrated on Tohoku Hospital Pediatrics-1 (THP1)-Blue-CD14 (THP1) human monocyte cells infected with HIV-1. After treatment twice with 200 µg/ml of PSP for six days, inhibition of viral replication of approximately 61% was found. In human peripheral blood mononuclear cells (PBMCs) obtained from healthy individuals and subsequently infected with HIV-1, PSP reduced viral replication by 45% to 87%. Additionally, PSP has been shown to promote the production of antiviral chemokines (RANTES, MIP-1α/β, and SDF-1α) that block HIV-1 co-receptors in THP1 cells and human PBMCs [47].

In preliminary randomized studies, in a group of 41 people infected with human papillomavirus (HPV) (serotype 16 and/or 18), mixtures of *T. versicolor* and *Ganoderma lucidum* were used. The fungi were obtained from cultures on birch, aspen and willow bark, and the obtained mycelia were dried, ground and placed in 200 mg capsules. After two months of treatment, the number of HPV-infected patients decreased by 88%.

In cell cultures, *T. versicolor* mycelium also had potential antiviral activity against the H1N1 influenza virus (strain A/FM/1/47) and HSV-2 virus (strain BH). For both viruses, the neutralization index was ID_{50} = 6.0, and the half-maximal effective concentration (EC_{50}) was 0.077 mg/ml [48]. Also, β-glucan (β − (1 → 3, 1 → 4)-glycosidic bonds) obtained from *T. versicolor* has been shown to be active against influenza virus H1N1 (A/Puerto Rico/8/34) and H9N2 (A/duck/Xuzhou/07/2003). Studies were conducted on infected mice and chicks who were orally administered β-glucan with a dose (200 or 400 µg per animal) for 14 days. Improved survival of animals and reduced lung viral titers have been found [49].

Various extracts (ethanol, ethyl acetate, chloroform and water) of *T. versicolor* show weak antibacterial activity against *Bacillus subtilis*, *Staphylococcus aureus*, *Enterococcus faecalis*, *Escherichia coli* and *Pseudomonas aeruginosa*. In the disc diffusion method, zones of growth inhibition (ZOI) were between 5.33 and 10.33 mm [50]. No activity was found against *Escherichia coli*, *Salmonella typhimurium*, *Staphylococcus epidermidis* and *Bacillus subtilis* [51].

Ethanolic extracts of *T. versicolor* mycelia showed weak antifungal activity. The minimum inhibitory concentration (MIC) value was 8 mg/ml for *Candida krusei* and 32 mg/ml for *C. albicans* and *Aspergillus glaucus*. No activity was found against *Candida parapsilosis*, *Aspergillus flavus* and *A. fumigatus* [52]. Other studies have also demonstrated the weak activity of *T. versicolor* extract against C. albicans with ZOI 5.67 to 9.00 mm [50]. In one study was presented a lack of effect against *C. albicans* but was activity on *Saccharomyces cerevisiae* (ZOI < 10 mm) [51].

The presented above results are shown below in Table 1.

4.3 Anticancer properties

The mushroom extracts are utilized as adjuvants in cancer patients and are also employed for cancer prevention [54, 55], anti-aging, and viral infection support. Some researchers propose that these extracts may potentially lower the risk of secondary malignancies caused by radiotherapy and cytotoxic chemotherapy in patients.

In Japan and China, these polysaccharide peptides are used as anticancer agents in conjugation with surgery, chemotherapy and radiation [56]. A study done by Roca-Lema et al. (2019), found the PSK to inhibit the growth of human colon cancer cells. While other researchers found that PSK also improve the treatment of colorectal or intestinal cancers when combined with chemotherapy [57, 58].

Moreover, PSK prevents human colon cancer cells from proliferating and spreading. *Coriolus versicolor* glucan, a different polysaccharide found in turkey tail mushrooms, inhibits certain cancers by boosting the immune system.

PSK exhibits anti-invasion activity by downregulating invasion factors (TGF-β1, µPA, MMP-2, and MMP-9) in pancreatic cancer cell line (NOR-P1) and gastric cancer cell line (MK-1P3), without impacting cell viability, proliferation, or adhesion [59].

Table 1 Antimicrobial activity of T. versicolor

Compound/s	Target microorganisms	Active concentration	References
Polysaccharide krestin (PSK)	HIV-1, HIV-2, HSV-1, HSV- 2, HTLV-1	Active concentration not specified	[42, 43]
Polysaccharopeptide (PSP)	HIV-1	IC_{50} = 150 µg/ml for interaction between HIV-1 gp120 and the CD4 receptor, dose of 62.5 nM (IC_{50} = 6.25 µg/ml) for inhibition of recombinant HIV-1 reverse transcriptase	[46]
Polysaccharopeptide (PSP)	HIV-1	200 µg/ml twice for six days for inhibition of viral replication	[47]
Mixtures of *T. versicolor* and *Ganoderma lucidum* mycelia	HPV (serotype 16 and/or 18)	200 mg capsules/day by two months decreased the number of HPV-infected patients by 88%	[53]
Mycelium	H1N1 influenza and HSV-2 virus	ID_{50} = 6.0, EC_{50} = 0.077 mg/ml	[48]
β-glucan	H1N1 and H9N2 influenza viruses	200 or 400 µg per animal for 14 days improved the survival of animals and reduced lung viral titers	[49]
Various extracts	*Bacillus subtilis*, *Staphylococcus aureus*, *Enterococcus faecalis*, *Escherichia coli* and *Pseudomonas aeruginosa*	ZOIs between 5.33 and 10.33 mm	[50]
Ethanolic extracts of mycelia	*Candida krusei, C. albicans, Aspergillus glaucus*	MIC values 8–32 mg/ml	[52]
Extract	*C. albicans*	ZOIs 5.67 to 9.00 mm	[50]
	Saccharomyces cerevisiae	ZOI < 10 mm	[51]

Additionally, *T. versicolor* mycelium ethanol extracts have shown to have anti-melanoma cell activity [60]. *Trametes* fungi species have anti-tyrosinase activity [61, 62] and *T.versicolor* enzymes such as laccases, lignin peroxidase, and manganese peroxidase have melanin decolorizing properties [63]. In view of this, turkey tail extracts can also be used in products for skin pigmentary disorders.

4.4 Antioxidant effects

Many findings of different studies found more than 35 different polyphenolic compounds in the *T. versicolor* mushroom extracts, and the most abundant flavonoids are quercetin and baiclein [10]. These compounds act as antioxidants and promote immune system activity by stimulating the release of different protective compounds like cytokines and act as antioxidants [64]. Therefore, these antioxidants reduce inflammation and cause the production of molecules that are protective, which helps to maintain a healthy immune system. For instance, compounds like quercetin inhibit the release of pro-inflammatory enzymes like cyclooxygenase and lipoxygenase while stimulating the creation of immune-protective proteins like interferon-γ [65]. Additionally, clinical benefits are brought by protein-bound polysaccharides such as PSK and PSP found in the fruiting body of turkey tail mushrooms [15, 66, 67]. The activation and inhibition of certain immune cells as well as the suppression of inflammation are both influenced by the strong immuno-stimulating capabilities of PSK and PSP.

PSK reduces oxidative stress in tumour-bearing rats, with administration of 50 mg/kg after 12 days of tumour development resulting in a significant decrease in superoxide release from red blood cells. In colon and gastric cancer, PSK at a dosage of 3 g/day effectively lowers oxidative stress levels. When combined with anticancer agents, PSK acts to counteract the generation of oxygen-free radicals produced by these agents [68].

Another important function, is its role in elevated levels of antioxidant enzymes in the brain as demonstrated in experiments done in mice in combination with Ginkgo biloba extract. Their brain tissue had lower expression levels of certain inflammatory markers [69].

Additionally, since turkey tail extracts have antioxidant activities [10, 70], they can be used in cosmetic products to treat free radical-induced oxidative damage on human skin [71]. Chong et al., 2018 showed that turkey tail extracts suppressed the ultraviolet B irradiation-induced cellular senescence in human keratinocytes (HaCaT) cells.

4.5 Hepatoprotective effects

PSK exhibits hepatoprotective effects and potential chemo-preventive properties against liver cancer [72, 73]. Two derivatives of polyoxygenated ergosterol demonstrate in vitro cytotoxic action against hepatoma cells. PSP reduces the binding affinity of [14C]-paracetamol to liver microsomes by 25% in rats when given intraperitoneally for 7 days at a dosage of 300 mg/kg/day, and it also dramatically lowers serum glutamic-oxaloacetic transaminase levels. However, PSP does not reverse the depletion of glutathione following a toxic dose of paracetamol [74].

In vitro studies related to the high content of phenolic compounds, suggest *T. versicolor* to have a strong antioxidant potential and protect DNA from free radical's damage [31]. Studies on animals [56, 75], suggested that *T. versicolor* extracts exert their hepatoprotective effects through the regulation of the immune response to free radicals. This is done by enhancing levels of antioxidant enzymes and improving the liver's role in detoxifying toxins like carbon tetrachloride (CCL4) [76].

4.6 Cardiovascular activities

T. versicolor derived glycoprotein exhibits antiplatelet, analgesic, antipyretic, antihyperlipemic, antiarrhythmic, anti-inflammatory, and vasodilating effects, demonstrating potential against hypertension and thrombosis [5]. Additionally, it improves proteinuria, controls prostaglandin formation, and reverses nephron disorders. PSK activates the gene for peritoneal macrophage colony-stimulating factor (M-CSF), preventing oxidative damage to macrophages and minimizing foam cell transformation during atherogenesis. Through the activation of mRNA transcription, PSK increases the activity of superoxide dismutase (SOD) and glutathione peroxidase [77]. Additionally, when PSK, IFN-, and LPS are used to excite macrophages, it enhances nitric oxide (NO) -induced macrophage apoptosis, inhibits oxidized LDL (oxLDL)-induced macrophage apoptosis, and stimulates the production of inducible nitric oxide (iNOS) mRNA [78].

4.7 Effects on gut microbiome

Other benefits from *T. versicolor* extracts, is supplying the gut with helpful bacteria (prebiotics). Treatment with *T. versicolor* extracts has a positive effect on the gut microbiome [29]. Yu et al. [79] found that treatment with *T. versicolor* extract modified the gut bacteria by increasing the population of *Bifidobacterium* and *Lactobacillus* whilst decreasing harmful bacteria like *Clostridium* and *Staphylococcus*. These healthy bacteria improved intestinal symptoms like diarrhea, reduced cholesterol, lower risks of certain cancers, enhance immune system, and improved digestion. This important function, may be due the *T. versicolor* extract contents of beta-glucan [80] and polysaccharides. Beta-glucan is indigestible material and cannot cross the lining of the gut, so it may be a source of prebiotics that may contribute in the composition of microbiome [81].

5 The ligninolytic enzyme system in turkey tail mushrooms and their applications

T. versicolor has a complex enzymatic system. They secrete different enzymes to degrade the lignocellulose of wood in lignin, cellulose, and hemicellulose. The ligninolytic enzymes are laccase (Lacc), lignin peroxidase (LiP), and manganese peroxidase (MnP) and degrade lignin the second most abundant biopolymer on earth. Lignin is composed of phenylpropanoid units (coniferyl alcohol, sinapyl alcohol, and paracoumaryl alcohol) linked by covalent bonds. Coniferyl alcohol, sinapyl alcohol, and paracoumaryl alcohol are phenolic compounds with interesting biological activities. Other enzymes produced by turkey tail are extracellular hydrolases (acid phosphatase, β-glucosidase, β-galactosidase, and N-acetyl-β-glucosaminidase) also carboxymethyl cellulases, and avicelases. Hydrolases degrade cellulose and hemicellulose.

The lignolytic enzymatic system breaks down diverse xenobiotic compounds and dyes [82]. *T. versicolor* laccase extracts have been utilized for wastewater treatment to decompose triclosan [83], bisphenol A, sodium diclofenac, sulfonamides, ibuprofen, carbamazepine, endocrine disrupting chemicals, dyes decolorization, heavy metals, polycyclic aromatic hydrocarbons (anthracene, benzo[α]pyrene, and phenanthrene) [84, 85], aflatoxins, bisphenol A, polyethylene 86], Uv-filters, pesticides and phenolic compounds [87].

6 The laccases enzymes in turkey tail mushrooms and their applications

Laccases are a group of enzymes widely distributed in bacteria, fungi (mostly white-rot fungi), plants, and insects. Fungi laccases have high redox potential compared to other laccases [88]. Laccases (benxendiol) contain four coppers and oxidase polyphenols using oxygen as an electron acceptor and they release only water as a by-product and do not produce reactive oxygen species (ROS). Laccase substrates are aromatic compounds containing hydroxyl and amine groups. Laccase activity is similar to other copper-containing enzymes such as tyrosinases. The expression of laccase is regulated by copper and nitrogen. Plant laccases play crucial roles in both the wound-healing system and the lignification process. On the other hand, fungi laccases are primarily engaged in the degradation of lignin. Laccases can be used as green catalysts and interactive biomolecules in wound dressing hydrogels. Laccases are used to cross-link different polymers (proteins and carbohydrates) with different chemical compounds with antioxidant, antimicrobial, and anti-inflammatory activities to improve their functional properties. Chen et al., 2022 created a biodegradable film with improved mechanical properties and antioxidant activity using chitosan cross-linked with tea polyphenols with laccase as a catalyst. Rocasalbas et al., 2013 prepared bioactive hydrogel dressing with antibacterial activity against *Pseudomonas aeruginosa* and *Staphylococcus aureus* using laccase crosslinking of chitosan/gelatin with *Hamamelis virginiana* polyphenols. Huber et al. [89] produced laccase-synthesized phenolic -O-carboxymethyl chitosan hydrogels with anti-inflammatory and antioxidant properties. The laccase effect was tested on different food products and laccase showed to have a pro-oxidant effect on vegetable oils.

Laccases are also used as a whitening agent [63, 90]. Miao et al. [62] showed than LiP has a higher decolorization activity on eumelanin and pheomelanin of skin and hair compared with Lacc and MnP. Tyrosinase mycelar extracts

from wood-decay mushrooms (Ganoderma applanatum, Laetiporus sulphureus and Trametes versıcolor also had tyrosinase ınhibition activity.

7 Future prospects and concluding remarks

In conclusion, the comprehensive review underscores the profound potential of *T. versicolor* as a multifunctional natural resource. Through an intricate exploration of its diverse bioactive constituents, including polysaccharides, phenols, triterpenes, and enzymes, this study unveils the intricate mechanisms underlying its wide-ranging therapeutic properties.

The elucidation of its therapeutic physiological mechanisms aligns with the mushroom's historical use in traditional medicine and propels it into modern healthcare considerations. Furthermore, the spotlight on enzymatic constituents and their applications emphasises the mushroom's promising role in biotechnology and manufacturing.

By synthesizing recent research, this review bridges the gap between traditional knowledge and contemporary understanding, affirming turkey tail mushroom's place as a rich source of bioactive agents. The synergy of its health-promoting and industrial potentials accentuates the importance of continued exploration for innovative therapeutic strategies and sustainable technological applications.

Looking ahead, the path for future research unfolds with a call to unravel mechanistic intricacies at the molecular level. Extensive clinical trials are urged to validate therapeutic efficacy and determine optimal dosage regimens. Exploring synergies among bioactive compounds, especially in combination therapies, opens new avenues for innovation. The biotechnological applications of enzymatic constituents present exciting prospects for integration into diverse industrial processes. Optimization of cultivation methods and standardization practices becomes paramount for ensuring a reliable and reproducible supply of bioactive compounds. Simultaneously, a comprehensive safety assessment is crucial to establish guidelines for consumption and application.Ultimately, this comprehensive review not only deepens our comprehension of turkey tail mushroom's capabilities but also inspires further investigation into its untapped possibilities, fostering avenues for both holistic healthcare advancements and progressive industrial breakthroughs.

Author contributions RB contributed to the conceptualization of the manuscript. EC supervised this project. EC, BB, OMA, EA and TMK contributed to the material preparation. BB, OMA, EA and TMK performed the literature search. The methodology, first and final complete drafts of the manuscript as well as revisions and editing of the manuscript was done by Emma Camilleri. All authors read and approved the final manuscript.

Funding This research did not receive any specific grant from funding agencies on the public, commercial, or not-for-profit sectors.

Data availability No data was used for the research described in the article. No data associated in this article has been deposited into a publicly available repository.

Declarations

Competing interest The authors declare that there are no conflicts of interest.

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