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How does the addition of mushrooms and their dietary fibre affect starchy foods

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A B S T R A C T

Mushrooms contain multiple bioactive compounds of which dietary fibre is a representative type. Fortification of extracted or naturally derived dietary fibre in staple starchy foods constitutes a strategy to increase fibre intake in terms of cardiovascular disease and other metabolic diseases. Food matrix is viewed as a physical domain containing nutrients in which interactions and behaviours are different from those in isolation or free state. The nutritional effect of mushrooms' addition in the starchy food matrix is reviewed together with the alterations of cooking properties. Prospective studies include nutrients bioaccessibility due to the interfere of dietary fibres in consideration of their types and quality. The future approach to shaping microbial colonisation in the digestive tract through metabolites such as short-chain fatty acids from dietary fibres is required to sustain host physiology and health.

1. Introduction

Mushrooms have been consumed for centuries due to their unique taste, aroma, texture characteristics, as well as their nutritional values. Besides, their pharmaceutical properties are of interest in terms of consumption by humans. According to data sourced from the Food Agriculture Organization of the United Nations [1], the total world production of cultivated mushrooms reached nearly 9 million tons in 2018. The most produced species is the *Agaricus bisporus* (white button mushroom), followed by *Lentinula edodes* (shiitake), *Pleurotus ostreatus* (oyster mushroom) and *Flammulina Velutipes* (golden needle mushroom). Approximately 45% of mushrooms are culinary-processed in their fresh form, as the fresh mushrooms are easily perishable with short shelf life (1-3 days) at ambient temperature [2]. Rapid post-harvest deterioration, such as browning, weight loss, and texture changes, limits mushrooms' distribution and marketing [3]. In the post-pandemic era of SARS-CoV-2 (COVID-19), consumers now have become focused on using their diets to improve their intake of antioxidant activity [4]. It is essential to utilise dried mushrooms to develop added-value coproducts and evaluate their nutritional values and functionalities in terms of human health.

Starchy foods represent one of the most consumed staple foods as the major energy intake for human's daily diets. Despite their critical function in human nutrition, starchy foods have come to be unfavourable in recent years since excessive intake of highly processed starch has been epidemiologically associated with a variety of adverse health consequences, including diabetes and obesity [5]. The fortification with natural phytochemicals as food additives in staple food products (starch-based foods) is on the road, with the potential for great health benefits, including manipulating low postprandial glycaemic response effects and increasing the intake of antioxidants. The addition also affects the amylose and amylopectin molecular structures, the rheology of foods processing and the

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end-use quality. Multiple studies have been done on developing β-glucan-enriched compounds from cereal sources such as oat and barley brans and incorporating them into baked, dairy, and confectionery foods [6]. As mushrooms are a great source of dietary fibre, they could be prepared as nutrient-rich foods for personalised nutrition, with consumer preference for healthy foods and the increasing demand for plant-based food.

In this mini-review, types of dietary fibre sourced from mushroom have been summarised. The impact of the addition of mushroom and their dietary fibres into mushroom-starchy foods was discussed from aspects including texture, cooking properties, and food acceptability to nutritional characteristics and biological functionalities. Digestive properties of starch and nutrients bioavailability from starchy foods have been expanded with proposed mechanisms and future directions.

2. Mushroom dietary fibre

Mushrooms are a rich source of dietary fibre. Compared to other conventional sources of dietary fibre, such as cereals, legumes, fruits and vegetables, mushrooms are underutilised [7]. The consumption of edible mushrooms as part of the daily diet can provide 25% of the recommended dietary intake of dietary fibre [7].

In 2001, the American Association of Cereal Chemists (AACC) defined dietary fibre as the edible part of plants or analogous carbohydrates, which resists digestion and absorption by the human small intestine, and is fully or partially fermented in the large intestine [8]. Dietary fibre includes polysaccharides, oligosaccharides, lignin and related plant substances. Mushroom dietary fibre is constituted mainly by water-insoluble ones (IDF), with chitin and β-glucans being the most representative ones; whilst the level of water-soluble ones (SDF) is usually less than 10% of dry weight.

Table 1
The content of glucans of edible mushrooms (g/100 g dw) [9].

Mushrooms	Mushroom parts	All glucans	α-Glucans	β-Glucans
A. bisporus (white button mushroom)	cap	10.05	1.55	8.61
	stem	14.96	2.67	12.30
L. edodes (shiitake)	cap	20.54	0.76	19.78
	stem	26.75	1.44	25.31
P. ostreatus (oyster mushroom)	whole	25.64	1.41	24.23
P. eryngii (king oyster mushroom)	whole	19.24	3.92	15.32

Note: All glucans: α-glucans and β-glucans.

Other polysaccharides, such as chitin, are found in the mycelia of mushrooms. With 4.69 g of chitin per 100 g (dry mass), *A. bisporus* contains less chitin in its fruiting body than its mycelia (9.60 g/100 g). In contrast, the chitin content is significantly higher in the fruiting body than in the mycelia of *F. velutipes* [10]. Other species have comparable amounts of chitin in their fruiting bodies and mycelia (Table 2).

3. Changes of cooking properties and texture in starchy foods

Table 3–5 summaries the changes in the physical texture, cooking properties of starchy foods such as bread, cookies, biscuits, muffins, and 3D printed snacks when incorporated with mushrooms or dietary fibre rich fractions. Nutrients in foods are dispersed as part of complex microstructure, not in the free form or dispersed homogeneously. Food matrix has been described as the complex assembly of components, including their physically and chemically interactions, release, mass transfer, accessibility, and digestibility [11]. Hydrated wheat gluten is referred to as a protein network that holds starch filler particles; they interact with each other and impart unique properties to starchy products [12]. Due to ease of cooking, noodles and pasta are popular staple foods and have been chosen as model food in several recent studies (Table 3). Although gel and liquid matrix were listed in the food matrix and many related studies have been done on dietary fibre and starch to explore their pasting properties and interactions, these studies were not included in this mini-review as which may not involve factors considering food processing and cooking properties in real foods consumed.

In the analysis of noodles' cooking properties, mushroom fortification (5%, 10%, 15%) led to a lower swelling index and water absorption index than white salted noodles [13]. Oyster mushroom noodles had a significantly higher water absorption index than shiitake noodles and white button mushroom noodle at each inclusion level. A possible explanation for these results is the higher dietary fibre content of oyster mushroom noodles than white button mushroom fortified noodles, illustrating that fibre content, especially the insoluble dietary fibre composition of mushrooms, has a vital role in determining the cooking qualities of noodles. In the correlation analysis in the study of Wang et al. [13], the significant negative correlation of dietary fibre and water absorption index was observed as well as in the spaghetti fortified with pollard [14]. The reason could be insoluble dietary fibre competes for available moisture with the starch in the foods network.

Other proposed molecular interactions of dietary fibre and starch are hydroxyl groups and hydrogen bonds during gelatinisation, which affects the water absorption behaviour, moisture migration, and redistribution of foods. The interactions between polysaccharide and starch have been investigated in multiple studies, and gel and liquid matrix system were normally involved [15,16]. Limited studies have been done between mushroom fibres and real foods. In the study by Kim et al. [6], the β-glucan enriched fraction from King oyster mushroom (*P. eryngii*) was studied in the model of wheat pasta, reducing the swelling index and water absorption when the level of beta-glucan was higher than 4%.

Cooking loss is a direct indicator of cooking quality by both consumers and the industry. It is calculated as the percentage of the residue in the weight of the starting material. In the analysis of cooking properties, the shiitake enriched noodles had a higher cooking

Table 2
Chitin contents in mushrooms (g/100 g dw) [10].

Chitin contents	*A. bisporus* (white button mushroom)	*L. edodes* (shiitake)	*P. ostreatus* (oyster mushroom)	*P. eryngii* (king oyster mushroom)	*F. velutipes* (golden needle mushroom)
Chitin (g/100 g dw) in mycelia	9.60	2.49	0.82	3.56	1.21
Chitin (g/100 g dw) in fruiting	4.69	1.87	0.76	3.16	9.83

loss (6.02–9.02 g/100 g) than the other two kinds of mushroom noodles, with the values ranging from 4.96 g/100 g to 6.52 g/100 g. The increase of cooking loss in pasta or noodles might result from the weakening of the gluten network [17].

Hydrogen bonds and water competition between starch granules and mushroom proteins also account for the alteration of products physical texture. The highest addition level of mushroom was 25% into the wheat flour-based 3D-printed snacks by the study of Keerthana et al. [18]. Physical rheology index, including springiness, cohesiveness, and gumminess, were improved [18]. Hardness was decreased compared to the wheat dough and mushroom dough before 3D printing. This was due to the dough formation properties by wheat proteins [19]. But in the β-glucan fortified foods, similar reduction was not reported instead of an increase of the hardness of semolina and wheat flour based pasta [6] and baked cakes [20]. This could be expected as dietary fibre acted as the structure building ingredients and the competition of water between dietary fibre and starch in the network [6].

Elasticity was found to be negatively correlated with soluble dietary fibre [13]. A similar negative correlation was observed between hardness and SDF in breads [21]. In a detailed study of starch and polysaccharides from shiitake, the elasticity was determined by the molecular weights of polysaccharides. High molecular weight polysaccharides would inhibit the swelling of trapped starch granules leading to a reduction of dough elasticity [22].

4. *In vitro* digestion of starchy foods by mushrooms and mushroom dietary fibre

Mushroom stems usually contain more dietary fibre than caps. Oyster mushroom stem and shiitake stem had higher insoluble dietary fibre and total dietary fibre than other groups [13]. If comparing results obtained in studies of Wang et al. [23] and Wang et al. [13], all three types of mushrooms fortified noodles had approximately twice as insoluble dietary fibre and total dietary fibre content as the wheat-flour based noodles, making them excellent sources of dietary fibre intake. The content of soluble dietary fibre, however, did not differ significantly among groups [13,23].

As noodles and pasta are traditionally wheat flour or semolina-based products, making them high in glycaemic response. Multiple studies have used non-wheat ingredients to produce noodles or pasta with higher nutritional values but lower glycaemic response than conventional noodles [23,24]. The fortification of mushrooms restricted the reducing sugars released during *in vitro* digestion significantly, negatively correlated with mushrooms derived insoluble dietary fibre ($P < 0.05$), suggesting the efficacy of mushroom stems over postprandial glucose release of foods. An *in vitro* starch digestion of the snack products showed that the black ear mushroom attenuated starch digestion, predicting a lower glycaemic response when consumed [25]. The reduction of glycaemic response was also observed in the model breads, where the 15% white button, 10% and 15% shiitake, and 15% porcini mushroom enriched breads had lower predictive glycaemic indexes than the control [21]. The entrapment of starch by mushroom dietary fibre reduced the gelatinisation under hydration-heat treatment. Non-gelatinised starch was less susceptible to digestion by α-amylase. In addition, soluble dietary fibre would increase the viscosity of intraluminal digesta, preventing contact with digestive enzymes [7]. These *in vitro* data may also need to be further clarified in the *in vivo* system combined with the conception of the gut microbiome as well as bile acids to expand the understanding of glycaemic response and glucose homeostasis.

5. Foods acceptability

Mushroom has unique and varied flours by numerous species, including anise-like, almond-like, floral, or fruity aromas and disagreeable odour represented by coal tar smell [2]. Products formulated with spicy and savoury flavour was preferred than sweet samples in the sensory evaluation of 3D print white button mushroom-wheat flour snacks [18].

The small amount of mushroom powder may bring a desirable aroma, colour, and flavour, while a higher amount may result in undesirable results [26]. In the β-glucan of king oyster mushroom fortified pasta, 2% had the highest acceptability [6]. In other baked food biscuits, 4% of Pleurotus sajor-caju obtained the highest scores of aroma, colour, flavour, and overall acceptance [26]. Fan et al. [27] has reported that up to 9% *Auricularia auricula* could be incorporated into baked foods without changing the sensory acceptance of breads [27]. Similarly, in a rice based extrudates study by Tepsongkroh et al. [28], increasing straw mushroom powder (from 0 to 10%) significantly ($P < 0.05$) increased liking scores of colour and mushroom flavour of extrudates but no significant ($P > 0.05$) differences were observed among 10%, 15%, and 20% [28]. Proper processing techniques on polysaccharides could improve the overall acceptance. In the cookies fortified by fermented *Agaricus bisporus* polysaccharides or unfermented (3%, 6%, 9%), fermented polysaccharides elevated the panellist acceptability, but the unfermented group decreased acceptability scores [29]. This could be due to the fermentation process enhancing the aroma and crispiness.

Specifically, colour is the first impression of foods and have a vital role in consumer acceptability. Compared with the colour of the barley dietary fibre, fibres sourced from *P. tuber-regium* and *P. rhinocerus* had higher values of lightness (L^*) but lower redness (a^*) and yellowness (b^*). The high degree of whiteness is considered as a technological advantage for mushroom dietary fibre if added to bakery food, since it is unlikely to produce off colours [30]. The colour change of mushroom powders into the food system may have a larger effect on the final product's colour. In the study of Wang et al. [13], uncooked noodles with either white button mushroom or oyster mushroom powder addition showed a decrease in lightness (L^*) and an increase in yellowness (b^*) compared to the control. A similar trend was also observed in cooked noodles, together with a significant decrease in redness (a^*) after mushrooms incorporation. The cooked noodles exhibited lower lightness, redness, and yellowness values, but a higher colour change (ΔE) than uncooked noodles. This was due to the darker control sample after the cooking process in which Maillard's reaction occurred. The colour change of white button mushroom was higher than that of oyster mushroom noodles at each inclusion level. Colour change of products from uncooked foods to cooked foods is normally caused by the enzymatically catalysed reaction, where the phenols undergo oxidative polymerisation to the dark brown or black pigment melanin [31].

Table 3
The effects of the addition of mushrooms on rheological, cooking, and microstructure properties of pasta and noodles.

Pasta/noodles	Mushrooms	Addition levels	Colour	Texture	Physical/thermal properties	Acceptability	Microstructure	Reference
Pasta (semolina)	Shiitake; white button (*A. bisporus*) and porcini mushroom (*B. edulis*)	5%, 10%, 15%	–	Increased cooking loss; decreased water absorption index and swelling index (porcini mushroom)	Increased ΔH values; reduced the degree of starch granule gelatinisation	–	More irregular and uneven compared with control; filament-like structures (15%)	Lu et al. [24], Lu et al. [41]
Semolina and wheat flour	*β*-glucan from King oyster mushroom (*P. eryngii*)	2%, 4%, 6%	Reddish brown coloured. lower L^* decreased; increased a^*	Viscosities reduced; increased hardness	–	2% had the highest acceptability	More regular network and porous structure	Kim et al. [6]
Noodles (wheat)	Shiitake mushroom (*L. edodes*)	5%, 10%, 15%	Reddish colour, L^* and b^* decreased; stem part had lower colour change (ΔE)	Higher firmness than control; but decreased with shiitake incorporation; increased elasticity (>10%)	water absorption index decreased;	–	–	Wang et al. [23]
	White button mushroom/oyster mushroom (*P. ostreatus*)	5%, 10%, 15%	Decrease in redness and lightness and increase in b^* (yellowness)	Decreased firmness	Water absorption index decreased; reduced optimal cooking time	–	–	Wang et al. [13]
Instant noodles	Oyster mushroom	2%, 4%, 6%, 8%, 10%	–	Peak viscosity and final viscosity, pasting temperature; increased (6%); and decreased (8%) extensibility (10%); breakdown strength	Increased water absorption, process recovery and solid loss increased when 10%	–	Overall acceptability of cooked noodles decreased (6%); 4% mushroom powder group was equally acceptable as the control sample	Arora et al. [42]

Table 4
The effects of the addition of mushrooms on rheological, cooking, and microstructure properties of breads.

	Mushrooms	Addition levels	Colour	Texture	Physical/thermal properties	Acceptability	Microstructure	Reference
Bread (wheat)	*A. blazei*, *H. erinaceus*, and *P. linteus*	5%	Decreased lightness and whiteness index, increased a^*, and b^*	Low loaf volume	decreased hardness, gumminess and more springiness and cohesiveness.	Low acceptability	–	Ulzijargal et al. [33]
	A. auricula (black ear mushroom)	0%, 2.5%, 5%, 7.5%, 10%	High water absorption and water holding capacity	–	High peak and final viscosities; reduced dough stability and elastic modulus	–	5% (*m*/*m*) had acceptable gluten network microstructure	Yuan et al. [43]
	P. eryngii (King oyster mushroom)	0%, 5%, 10%	Increased crust redness decreased of lightness and yellowness of bread; a of crust and crumb increased	Decreased bread height and softness, increased firmness	–	No statistically difference among breads of the overall assessment	Increased crumb void fraction and cell density	Gaglio et al. [44]
	White button, shiitake, porcini mushroom	5%, 10%, 15%	–	Reduced loaf volume, height and springiness	Increased water absorption capacity	–	5% Porcini mushroom had the largest bubbles among samples	Lu et al. [45]

Table 5
The effects of the addition of mushrooms on rheological, cooking, and microstructure properties of starchy foods.

Model foods	Mushrooms	Addition levels	Colour	Texture	Physical/thermal properties	Acceptability	Microstructure	Reference
Extruded food	Chestnut mushroom (*A. aegerita*)	5%, 10%, 15%	–	Low final viscosity	Water absorption index decreased; water solubility decreased	–	–	Brennan et al. [46]
	Black ear mushroom	5%, 10%, 15%	Decreased L^* and a^*, increased b^*	Decreased expansion ratio	Lower glycaemic index	–	–	Vallée et al. [25]
Cookies	*A. bisporus* (unfermented and fermented polysaccharide by *Lactobacillus plantarum*)	3%, 6%, 9%	Lower L^*, a^*, and b^*	Lower fracture strength and hardness	–	Fermented group elevated the panelist acceptability, but the unfermented group decreased acceptability scores	Aggregated spherical granules; fermented were more compact with continuous structures compared to unfermented	Sulieman et al. [29]
Biscuits	Pleurotus sajor-caju	4% 8%, 12%	–	Reduced pasting viscosity and gelatinisation degree	–	Reduced diameters of starch granules proportional to the mushroom powder added	4% had the highest scores of aroma, colour, flavour, and overall acceptance	Ng et al. [26]
Muffins (rice flour)	Shiitake mushroom	5%, 10%, 15%	Decreased L^*, a^*, b^* of crust and crumb; except for increased a^* of crumb	Decreased peak viscosity, trough viscosity, breakdown, final viscosity and setback viscosity	Increased hardness, chewiness, volume, and increased springiness	–	Decreased overall acceptability	Olawuyi et al. [47]
3D printed snacks (wheat flour)	White button mushroom	5%, 10%, 15%, 20%, 25%	20% decreased L^*, increased a^*, and b^* of post-processed samples	Decreased hardness, adhesiveness, and resilience; increased springiness, cohesiveness, gumminess and chewiness	–	–	Spicy and savoury products instead of sweet samples	Keerthana et al. [18]
Rice-based extrudates	Straw mushroom (*V. volvacea* (Bull. ex Fr.) Sing.)	10%, 15%, 20%	Decreased lightness	Increased true density, decreased expansion ratio and hardness	–	–	Increasing MP (from 0 to 10%) significantly ($P < 0.05$) increased liking scores of colour, mushroom flavour of extrudates	Tepsongkroh et al. [28]

6. Biological health benefits of mushroom-starchy foods

Most previous studies have been based on evidence using *in vitro* and *in vivo* models to substantiate the benefits of using isolated compounds or extracts to protect against oxidative stress and disease. Apart from dietary supplementation, whole foods rich in natural nutrients have been shed light upon due to their lower incidence and milder courses of viral infections [32]. Viral pandemics are characterised by elevated oxidative stress, which impairs the antioxidant status [4]. A balanced diet rich in antioxidants is critical for maintaining the immune system's optimum antioxidant state. Especially under the pandemic of COVID-19, there is a pressing need of using proper diets to improve their intake of antioxidant activity and boost their immunity.

Since mushrooms are natural products rich in fibre, they are also considered an excellent choice to be added to starchy foods, including bread, cakes and extrusion food. For example, mushroom mycelium could be incorporated into bread to increase antioxidant content [33]. Extruded snack foods with black ear mushroom (*A. auricula*) increased the total phenolic concentration and had a higher percentage of free radicals scavenging effect in a DPPH assay. An ORAC assay also revealed that black ear mushroom inclusion gave a high antioxidant activity [25].

The antioxidant abilities of shiitake mushroom into noodles at the level 15% had a three-fold increase than the wheat flour noodles, and the *in vitro* digesta of fortified noodles had continuously higher antioxidant abilities than the noodles [23]. These antioxidant abilities of noodles, including digesta in the intestine phase, were significantly positively correlated with insoluble dietary fibre, whereas no similar positive correlation was observed between antioxidant abilities and soluble dietary fibre [13]. Dietary fibre has been proposed to act as a carrier in the food matrix. Phenolics contained in the plants are usually conjugated with dietary fibre forming a complex. In the digestion process, the conjugated phenolics are released from the complex and thus turn to assessable antioxidants in the gastric intestinal tract. Insoluble dietary fibre, as evidenced by the above results, was able to boost antioxidant capacity even after intestinal digestion, as well as to quench oxidative radicals by surface interaction and protein [34].

Other biological functionalities include lipid regulation of dietary fibre. Dietary fibres can bind to bile acids and inhibit enterohepatic circulation, leading to decreased blood cholesterol [35]. Palanisamy and co-workers extracted the dietary fibre fractions from three edible mushrooms species. They found these dietary fibres showed bile acid binding capacity *in vitro*, although the total bile acids content in this study was quantified by the sum of only four bile acids [36]. It has been postulated that the IDF binds directly to bile acids to affect the cholesterol-lowering properties, and SDF could use its water-binding capabilities to increase chyme viscosity, thus reducing the diffusion rate of BAs [37]. Dietary fibre fractions from *P. ostreatus* was proved to have a cholesterol lowering effect and reducing hepatic triglyceride through *Dgat 1* gene. Whereas in the system of starchy foods, the studies of dietary fibre and bile acids with their interactions are limited and may need to be further explored.

7. Changes of nutrients bioavailability by dietary fibre

The consideration of bioaccessibility and bioavailability when claiming functionalised foods are required due to the animate nature of the digestive tract that cannot be replicated *in vitro* easily. It is still noteworthy that as mushrooms are rich in fibre, this may interfere with the mineral bioavailability. In the digestion process, dietary fibre has also been noted to interfere with the absorption of macronutrients and biomolecules, especially fat, some minerals and trace elements, largely due to mineral binding or physical entrapment. However, this adverse impact may be mitigated by colon fermentation of dietary fibres with gut microbe flora, thus releasing bound minerals and promoting colonic absorption [38]. A recent concept of dietary fibre has also been brought out that it serves as a platform for bringing bacteria and biomolecules, such as bile acids, into close proximity for later physiologically metabolism [39]. Therefore, more studies are needed to understand the role of fibre in nutrient uptake with plant- and process-specific fibres considering other inhibitors or enhancers in the food matrix, such as phytates and polyphenols.

8. Conclusion and future work

Fortification of foods with naturally derived dietary fibre constitutes an efficient strategy to increase fibre intake. In addition to regulating nutrients bioavailability, future nutritional studies are needed to decipher cellular and biological functionalities of dietary fibre on microbial ecology considering fibre qualities and sources. The precise and predictive modulation of fibres' fermentation to short-chain fatty acids was recommended as nutrition personalisation are needed among individuals [40]. A better understanding of naturally derived fibres and their biological functionalities with starchy foods will help develop nutrition approaches, targeting and reducing the incidence of chronic metabolic diseases.

Declaration of interests

The authors declare there is no conflict of interest.

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