

Kombucha from alternative raw materials – the review

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22 **Abstract**

23 Nowadays, people’s awareness about the role of diet in maintaining well-being and
24 good health has increased. Consumers expect that the products not only provide them with
25 essential nutrients but will also be a source of biologically active substances, which are
26 beneficial to their health. One of the “healthy trends,” which has appeared among the
27 consumers worldwide is kombucha, a tea drink with high antioxidant potential, obtained
28 through the activity of a consortium of acetic acid bacteria and osmophilic yeast, which is
29 also called “tea fungus.” Kombucha obtained from tea is characterized by its health-
30 promoting properties. Promising results in *in vitro* and *in vivo* studies have prompted research
31 groups from around the world to search for alternative raw materials for tea fungus
32 fermentation. Attempts are made to obtain functional beverages from leaves, herb infusions,
33 vegetable pulp, fruit juices or milk. This review focuses on describing the progress in
34 obtaining a fermented beverage and bacterial cellulose using tea fungus on alternative raw
35 materials.

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47 Keywords: tea fungus, kombucha, fermented beverages, fruit pomace, bacterial cellulose

48 **1. Introduction**

49 In recent years, consumer awareness about food quality and the role of diet in
50 maintaining good health has increased. People expect that food products will not only be a
51 convenient, ready to eat after minimal preparation, but will also be the source of essential
52 nutrients as well as substances positively affecting health and well-being. Therefore, a
53 continuous increase in demand for foods having desirable effects on the body has been
54 observed, affecting the rapid development of a new food market. Such products are currently
55 called “functional food.” This term was introduced in the early 1990s and defined as food
56 which provides not only basic nutrition but also exerts a positive effect on the human body by
57 being a source of biologically active substances. These compounds can reduce the risk of
58 certain diseases or slow down the ageing processes. The term “functional food” includes
59 traditional foods with naturally occurring bioactive substances (e.g. dietary fiber,
60 polyphenols), food with the addition of bioactive substances (e.g. peptides, antioxidants) and
61 derived food ingredients introduced into ordinary foods (e.g. prebiotics). Health claims about
62 the ability of functional food must be supported by significant scientific evidence
63 (Martirosyan & Singh, 2015).

64 The concept of functional food is derived from the philosophical tradition of the East,
65 in which there is no apparent difference between drugs and nutrition. A particular place in
66 this topic is occupied by fermented products that have been obtained since ancient times.
67 Fermentation is a method of food preservation, which allows extending the freshness of
68 products, as well as causing favorable changes in the bioavailability of active compounds. Of
69 particular interest are products, such as sauerkraut, kimchi, milk fermented beverages or
70 kombucha whose functional properties have been thoroughly tested and described in the
71 international literature (Hazra, Gandhi, & Das, 2018; Marco et al., 2017; Peñas, Martinez-
72 Villaluenga, & Frias, 2016).



73 This work focuses on the review of the knowledge about the properties of kombucha
74 beverages obtained from alternative raw materials, e.g. fruits, vegetables or herb infusions,
75 and their comparison with the characteristics of fermented sweetened tea. The paper also
76 describes the possibilities of using a waste product, bacterial cellulose created during the
77 preparation of a drink.

78 **2. Kombucha – fermented tea beverage**

79 Kombucha is a fermented beverage with a specific refreshing, sweet and slightly sour
80 flavor resembling carbonated cider. It is obtained from the sweetened medium, commonly
81 black or green tea, by the action of a consortium of acetic acid bacteria and osmophilic yeast
82 (so called “tea fungus”), which takes 7–21 days (De Roos & De Vuyst, 2018; Dickmann et
83 al., 2017; Kapp & Sumner, 2019). Tea fungus, in the form of a cellulosic biofilm, transform
84 the sugar and tea components into bioactive compounds with therapeutic effects.

85 *2.1. Characteristics of microorganisms in tea fungus*

86 Fermentation occurs rapidly after adding tea fungus to the sweetened tea. In this
87 cellulosic biofilm yeasts are present, among others: *Candida stellimalicola*, *Candida*
88 *tropicalis*, *Lachancea thermotolerans*, *Lachancea fermentati*, *Eremothecium cymbalariae*,
89 *Kluyveromyces marxianus*, *Pichia mexicana*, *Dekkera bruxellensis*, *Dekkera anomala*,
90 *Saccharomyces cerevisiae*, *Saccharomyces uvarum*, *Zygosaccharomyces bailii*,
91 *Zygorulaspora florentina* (Villarreal-Soto, Beaufort, Bouajila, Souchard, & Taillandier,
92 2018). In addition to yeast, bacteria are also present, including lactic acid bacteria (LAB)
93 from the genus of *Lactobacillus* sp. – *Lactobacillus kefiranofaciens*, *Lactobacillus nagelli*,
94 *Lactobacillus satsumensis* and *Lactococcus* sp. (Marsh, O’Sullivan, Hill, Ross, & Cotter,
95 2014). LAB delivered from kombucha can be considered as probiotics because they meet
96 most of the criteria for these: they have a high tolerance for bile salts and they are able to
97 survive in the human gut (Matei et al., 2018). However, the leading group of bacteria in tea



98 fungus, the most numerous, are acetic acid bacteria (AAB), mainly species from the genera
99 *Acetobacter* (*Acetobacter aceti*, *Acetobacter pasteurianus*, *Acetobacter nitrogenifigens*),
100 *Gluconacetobacter* (*Gluconacetobacter* sp A4, *Gluconacetobacter sacchari*,
101 *Gluconacetobacter oxydans*) and *Komagataeibacter* (*Komagataeibacter xylinus*,
102 *Komagataeibacter kombuchae*) (Chakravorty et al., 2016). Sometimes bacteria from the
103 *Propionibacterium* or *Enterococcus* genera are also isolated (Marsh et al., 2014). The
104 microbial community in tea fungus may vary between fermentations, but some of the species
105 remain unchanged (Chakravorty et al., 2016; Coton et al., 2017; Marsh, O’Sullivan, Hill,
106 Ross, & Cotter, 2014). According to some authors, the biodiversity of the tea fungus
107 ecosystems depends on the geographical and climatic conditions and on the types of wild
108 yeasts and bacteria that occur locally. Also, fermentation conditions affect the bacterial
109 ecosystem: a higher temperature promotes the growth of some bacteria genera e.g.
110 *Propionibacterium*, *Corynebacterium* as well as *Lactobacillus*, *Lactococcus*, or
111 *Streptococcus* (De Filippis, Troise, Vitaglione, & Ercolini, 2018).

112 The relationship between yeast and bacteria in tea fungus consortia is complex. At the
113 same time, there may be a commensal and amensal association among them. Substances
114 secreted extracellularly by microbes may stimulate or inhibit the growth of accompanying
115 microflora. Their interactions should be subjected to comprehensive analysis to make it
116 possible to understand this phenomenon of coexistence and close dependence of different
117 microorganisms in one ecological system (Villarreal-Soto, Beaufort, Bouajila, Souchard, &
118 Taillandier, 2018).

119 2.2. Sucrose metabolism by tea fungus consortia

120 Initially, sucrose, originating from the medium (sweetened tea), is hydrolyzed to
121 glucose and fructose by invertase (β -fructofuranosidase, EC 3.2.1.26), produced mainly by
122 *Saccharomyces cerevisiae* as well as other yeasts species (Kulshrestha, Tyagi, Sindhi, &



123 Yadavilli, 2013). This enzyme is active in an acidic pH (3.5–5.5); therefore, sucrose
124 hydrolysis is not stopped by the organic acids formed at a later stage. From the resulting
125 monosaccharides, yeasts synthesize ethanol. The maximum concentration of reducing sugars
126 and ethanol occurs on day 7 of fermentation. Over the following days, the content of ethanol
127 decreases as a result of oxidation to acetic acid by AAB. In addition, AAB enzymatically
128 oxidizes D-glucose at the C-6 position and the aldehyde group of the β -D-glucose at the
129 position of C1, resulting in the formation of significant quantities of glucuronic acid and D-
130 glucano- δ -lactone, respectively. Microbial enzymes hydrolyze this latter metabolite into
131 gluconic acid. At the same time AAB, mainly *K. xylinus* due to its specific metabolism
132 produce cellulose from glucose (Amaniampong et al., 2017; Chakravorty et al., 2016;
133 Jayabalan, Malbaša, & Sathishkumar, 2017; Ramachandran, Fontanille, Pandey, & Larroche,
134 2006; Villarreal-Soto et al., 2018). The roles of other microorganisms during fermentation are
135 still not precisely described. Some of them excrete their metabolic products and affect each
136 other. For example, Yang et al. (2010) showed that bacteria from the *Lactobacillus* genus
137 have a positive effect on the growth of *Gluconacetobacter* sp. A4 and the production of D-
138 saccharic acid-1,4-lactone, an essential bioactive compound.

139 2.3. Chemical composition and biological activity of kombucha

140 The primary substrates for the production of kombucha beverages are green or black
141 sweetened tea. After fermentation, final products have a complex chemical composition and
142 contain several compounds i.e. organic acids, vitamins, active enzymes, polyphenols and a
143 variety of micronutrients (Kumar & Joshi, 2016). The composition of the beverages depends
144 on many factors, e.g. the raw materials used and the carbon source, the tea's concentration,
145 the microbial composition of the tea fungus, the time and temperature of fermentation and the
146 pH of the process. Any changes in these parameters impact on the quality of the final product,
147 its nutritional, biological and sensory properties. Even the hardness of the water used affects



148 the functional properties of the beverages. Kombucha obtained using water with a high
149 concentration of calcium ions had higher antibacterial activity against *Staphylococcus aureus*
150 than beverages achieved from water with a low content of calcium ions (Lawton & Kumar,
151 2016).

152 The dry weight of fresh tea contains about 0.5% of organic acids, mainly citric, malic,
153 tartaric, oxalic and succinic acids. During fermentation, microorganisms produce other
154 important acids: acetic, gluconic, glucuronic, L-lactic, malonic, pyruvic and usnic acids
155 (Villarreal-Soto et al., 2018). Acetic acid is produced in the highest concentration. It has been
156 shown that consumption of acetic acid in moderate amounts slows gastric emptying time,
157 blocks the action of the disaccharidases (enzymes hydrolyzing disaccharides into
158 monosaccharides) and increases glucose uptake by the liver and muscles which reduces its
159 level in the blood (Zubaidah, et al., 2018b). Additionally, it may also inhibit lipogenesis and
160 the cholesterologenesi pathway in the liver, so it is responsible for decreasing total
161 cholesterol, LDL cholesterol and triglycerides in serum (Zubaidah et al., 2018a; Zubaidah et
162 al., 2019).

163 Nonetheless, glucuronic acid is considered to be the principal therapeutic agent in
164 kombucha with the main role in liver detoxification by the process of glucuronidation (Coton
165 et al., 2017; Jayabalan et al., 2017; Martínez-Leal, Suárez, Jayabalan, Oros, & Escalante-
166 Aburto, 2018). Glucuronidation is based on the conjugation of glucuronic acid to the slightly
167 soluble or insoluble substrates, e.g. xenobiotics. This reaction is catalyzed by UDP-
168 gluconosyltransferases (EC 2.4.1.17). It is a detoxification process, which enables drugs to be
169 eliminated from the body through the excretory system. Glucuronidation occurs mainly in the
170 liver, but UDP-gluconosyltransferases are also found in other organs, e.g. kidneys, lungs and
171 ovaries and the prostate gland (Mróz & Mazerska, 2015). Fermentation at 30°C leads to
172 higher concentrations of gluconic and glucuronic acids than at 20°C. This is positively



173 correlated with the promotion of the growth of the leading producer of glucuronic acid,
174 *Gluconacetobacter saccharivorans*, at the higher temperature, while at the lower temperature
175 *K. xylinus* prevails in the fermentation (De Filippis et al., 2018).

176 DSL (D-saccharic acid-1,4-lactone) is created in kombucha beverages from D-
177 glucaric acid as a result of the activity of bacteria belonging to *Gluconacetobacter* sp.,
178 especially by *Gluconacetobacter* sp. A4. DSL is not found in unfermented tea. Its
179 concentration increases until the eighth day of fermentation, ranging between 58 and
180 133 mg/mL depending on the sample (Chakravorty et al., 2016; Martínez-Leal et al., 2018;
181 Yang et al., 2010). DSL is considered to be the compound behind the hepatoprotective and
182 hypocholesterolemic effects of kombucha (Bhattacharya, Gachhui, & Sil, 2013). Its
183 hepatoprotective mechanism is based on inhibition of the activity of β -glucuronidase, an
184 endogenic, human enzyme located in lysosomes, which hydrolyzes the complexes of
185 glucuronic acid with toxins, formed in the process of glucuronidation, making it difficult to
186 excrete them. DSL bonds with amino acids at the active site of the enzyme and blocks the
187 binding of substrate (Iqbal et al., 2018; Jamil et al., 2018). Additionally, DSL can prevent
188 hyperglycemia-induced hepatic dysfunctions by inhibiting liver apoptosis (Bhattacharya,
189 Gachhui, & Sil, 2013).

190 Tea is a rich source of polyphenols, whose amount and composition varies depending
191 on the type of tea. The polyphenols in the brewed green tea are mainly catechins, which
192 account for 30–42% of the dry mass. Green tea polyphenols belong to four major classes: (-)-
193 epicatechin, (-)-epicatechin gallate, (-)-epigallocatechin and (+)-epigallocatechin gallate
194 (Sharma et al., 2018). In the case of black tea, during the production process, these
195 compounds are oxidized and dimerized; therefore, the black tea polyphenols profile is
196 different and contains thearubigins, theaflavins, flavonols as well as catechins. The
197 concentration of the latter components is lower than in green tea (Ozdal et al., 2016; Sharma



198 et al., 2018; Warden, Smith, Beecher, Balentine, & Clevidence, 2001). It is well known that
199 polyphenols can prevent chronic diseases due to their antioxidative properties. Some of these
200 compounds were also shown to inhibit DNA methyltransferase 1 which may result in the
201 demethylation of promotor regions of tumor suppressor genes, which are usually
202 hypermethylated in tumor cells (Saldívar-González et al., 2018; Zhong, Xu, Reece, & Yang,
203 2016). Polyphenols are of particular interest to scientists because of their cytoprotective
204 effect on healthy cells and simultaneously cytotoxic effect on cancer cells (Brglez Mojzer,
205 Knez Hrnčič, Škerget, Knez, & Bren, 2016). During the tea fungus fermentation of sweetened
206 tea, polyphenols are modified, and as a result, the new compounds are formed. With the
207 extension of the fermentation time, the composition and concentration of polyphenolic
208 compounds in kombucha changes. This may be due to the action of microbial enzymes that
209 lead to the degradation of the complex tea polyphenols into simpler molecules, resulting in an
210 increase of antioxidant activity of the beverage compared to unfermented tea. Hydrolysis of
211 polyphenols during fermentation is probably caused by tannase, an enzyme extracellularly
212 produced by yeast and bacteria. As a result of tannase activity, epigallocatechin, gallic acid
213 and glucose are released from epigallocatechin gallate gallotannins, gallic acid esters and
214 epicatechin gallate. The products of this enzymatic reaction possess higher antioxidant
215 capacity than unhydrolyzed compounds (Baik et al., 2015; de las Rivas, Rodriguez, Anguita,
216 & Munoz, 2019). Other extracellular enzymes produced by the microbes present in tea
217 fungus, such as phytases and β -galactosidase, may also modify tea polyphenols. It was shown
218 that addition of β -galactosidase to olive mill wastewater caused the release of simple phenolic
219 compounds with high antioxidant activity from this raw material which is rich in polyphenols
220 (Hamza, Khoufi, & Sayadi, 2012). Additionally, during tea fungus fermentation, part of the
221 thearubigins from tea may be converted to theaflavin, which changes the color of the
222 beverage from reddish brown to light brown (Chakravorty et al., 2016).



223 Except for tea polyphenols in kombucha, isorhamnetin (O-methylated flavonol), a
224 derivative of quercetin, was detected. This polyphenol is present, among others in cocoa or
225 Ginkgo biloba, but not in tea. This suggested that tea fungus fermentation leads to the
226 formation of this compound. Isorhamnetin and catechins have bacteriostatic and bactericidal
227 activity (Bhattacharya et al., 2016; Li et al., 2016). The polyphenolic fraction of 14-day
228 kombucha containing mainly catechin and isorhamnetin showed strong antibacterial activity
229 against *Vibrio cholerae*. These polyphenols may act as prooxidants by generating oxidative
230 stress, which results in the degradation of bacterial cell membranes and leads to the inhibition
231 of bacterial growth in a concentration-dependent manner. This phenolic fraction did not show
232 a cytotoxic effect on human cells (Bhattacharya et al., 2018).

233 It has been shown that different carbon sources affect the total phenolic content in the
234 product. Aspartame inhibited microbial growth and, as a consequence, the fermentation
235 process did not proceed. Application of white or brown sugar as a carbon source during
236 fermentation caused intensive growth of tea fungus and resulted in a high content of
237 polyphenols in the final products. The use of honey as a carbon source results in a richer
238 chemical composition in the final product, with a high content of e.g. organic acids, essential
239 oils, alcohols, esters as well as polyphenols. Its original composition could lead to changes in
240 the pH and modification of the fermentation process, and thus to changes in the polyphenol
241 profile (Watawana, Jayawardena, Ranasinghe, & Waisundara, 2017).

242 Kombucha obtained from black or green tea is characterized by health-promoting
243 properties. This beverage, rich in bioactive components, has a number of pro-health
244 advantages: antimicrobial and antioxidant activity, as well as hepatoprotective and anticancer
245 effect. Promising results in *in vitro* and *in vivo* studies have induced research groups from
246 around the world to search for alternative raw materials for the tea fungus culture.

247 **3. Alternative raw materials for kombucha production**



248 Recently, in the world literature, there are more and more reports regarding using tea
249 fungus to create new fermented functional products from raw materials other than tea, e.g.
250 fruit or vegetable juices and cocktails, herbal or plant infusions, milk or food industry by-
251 products. Some of them contain carbohydrates, which the tea fungus uses as a carbon source
252 and in the fermentation process produce bioactive products with unique, pro-health properties
253 (Aspiyanto et al., 2016; Gaggia et al., 2018; Liamkaew, Chattrawanit, & Danvirutai, 2016;
254 Moreno-Jiménez et al., 2018; Vázquez-Cabral et al., 2017; Vitas, Cvetanović, Mašković,
255 Švarc-Gajić, & Malbaša, 2018; Yavari, Mazaheri-Assadi, Mazhari, Moghadam, & Larijani,
256 2017; Zubaidah et al., 2018a; Zubaidah et al., 2018b; Zubaidah et al., 2019). Depending on
257 the composition of the raw material, the properties of the products vary on. It seems that the
258 application of tea fungus to create new functional products based on various raw materials is
259 still an open issue. Examples of the use of alternative raw materials for the tea fungus
260 fermentation process found in the literature were collated and described below.

261 *Tea with additives*

262 Fermentation of sweetened green tea with the addition of cinnamon in the range 25–
263 75% (w/v) resulted in increased amounts of organic acids amounts and high antioxidants and
264 antimicrobial activity of the final products. These properties increased as the concentration of
265 cinnamon in the tea was increased. The strong antibacterial activity of kombuchas with
266 cinnamon is probably caused by the presence of cinnamaldehyde and eugenol derived from
267 the cinnamon. These components disrupt the lipid bilayer of the bacterial cell membrane and
268 cause higher permeability, which leads to extensive leakage of ions and important cell
269 compounds (Nuryastuti et al., 2009; Shahbazi, Hashemi Gahruie, Golmakani, Eskandari, &
270 Movahedi, 2018).

271 Kombucha made from black tea with the addition of 15% apple juice (v/v) after ten
272 days of fermentation had a higher polyphenols content than kombucha made from tea alone



273 because apple juice contains a significant amount of polyphenols. The alcohol and acid
274 content was also higher in apple-tea kombucha than tea kombucha. Further research should
275 optimize the process to reduce the alcohol and acetic acid content (Liamkaew et al., 2016).

276 Pollen collected by bees has antimicrobial, antioxidant, antimutagenic and anti-
277 inflammatory activity (Denisow & Denisow-Pietrzyk, 2016). It is also considered to exert
278 also antitumoral, immunomodulatory, cardioprotective and anti-diabetic effects. The pollen
279 grain wall has a complex structure resistant to degradation by digestive enzymes; therefore,
280 the bioavailability of the phytonutrients from it is limited. Fermentation by tea fungus may be
281 one of the methods of increasing the bioavailability of these valuable ingredients. After
282 30 days of fermentation of green tea with the addition of multi-floral pollen, the pollen grain
283 wall was weakened and release of nutrients into the fermentation liquid took place. In the
284 final result, fermented beverages containing pollen had higher polyphenol content than those
285 without pollen. The addition of pollen also led to an increase in the LAB population,
286 especially fructophilic LAB, which are the part of its microbiota. The final product was
287 characterized by a high concentration of lactic acid and low content of gluconic acid in
288 comparison to the product without pollen. This may suggest that LAB may inhibit the growth
289 of AAB by way of competition. However, the addition of pollen indirectly induces the
290 formation of short chain fatty acids (SCFA) in a beverage. SCFA are formed by the microbial
291 fermentation of carbohydrates, such as dietary fiber. SCFA are bioactive molecules, called
292 postbiotics, produced by bacteria, including LAB. Postbiotics refers to the metabolic products
293 or by-products secreted by a bacteria cell. They may have anti-inflammatory,
294 immunomodulatory, hypocholesterolemic and antioxidant activities (Aguilar-Toalá et al.,
295 2018; Uțoiu et al., 2018).

296 *Infusions*



297 Coffee contains over a thousand bioactive compounds, some of which have potential
298 therapeutic effects. It is an important source of antioxidants, mainly caffeine, caffeic acid and
299 its derivative, chlorogenic acid, diterpenes, cafestol and kahweol. It is well known that coffee
300 shows pro-health properties such as antioxidant, anti-inflammatory, antifibrotic, or anticancer
301 activity. Fermentation of black tea enriched with CoffeeBerry® extract resulted in final
302 beverages with a higher polyphenol content and higher antioxidant activity than black tea
303 kombucha (Essawet et al., 2015). Tea fungus fermentation also takes place in sweetened
304 coffee extract without tea. Seven-day fermentation of coffee infusions improves their
305 therapeutic properties. It was observed that coffee kombucha has higher antioxidant activity
306 than a coffee infusion as well as a higher chlorogenic and caffeic acid content. The fermented
307 coffee infusion inhibited the activity of starch hydrolase to a greater extent than an
308 unfermented beverage. Therefore, it is stated that coffee kombucha can delay starch digestion
309 and reduce the amount of glucose in the blood. In this way, the fermented beverage is useful
310 in maintaining health and wellness (Poole et al., 2017; Watawana, Jayawardena, &
311 Waisundara, 2015; Yamagata, 2018).

312 Herbal infusions have been used for many years in the home treatment of various
313 ailments. Their health-promoting activity can be increased after the fermentation process
314 carried out by the tea fungus. Velićaniski et al. (2014) showed that kombucha from
315 sweetened lemon balm (*Melissa officinalis* L.) had greater antioxidant activity than a non-
316 fermented infusion. The same relationship has been demonstrated for kombucha from winter
317 savory (*Satureja montana* L.) (Cetojevic-Simin, et al., 2008). Both types of fermented
318 beverages also showed antibacterial activity against many gram-positive and gram-negative
319 species of pathogenic bacteria (Velićaniski et al., 2014; Cetojevic-Simin, et al., 2008). In
320 addition, kombucha from winter savory inhibited the growth of HeLa cells (cervix epithelioid
321 carcinoma) by 20% (Cetojevic-Simin, et al. 2008).



322 Yarrow (*Achillea millefolium*) is a widely used medicinal plant. It has astringent,
323 antiseptic and anti-inflammatory properties and is used for the treatment of wounds, burns,
324 hemorrhages, digestive disorders, menstrual cramps or flatulence. It contains over a hundred
325 bioactive compounds, e.g. achilleine, apigenin, azulene, camphor, coumarin, menthol,
326 quercetin, rutin, succinic and salicylic acid (Tadić et al., 2017). Yarrow extract, obtained as a
327 result of supercritical extraction, fermented by tea fungus showed higher antioxidant activity
328 and a higher content of organic acids (acetic, succinic, malic and oxalic) in comparison to the
329 yarrow infusion fermented by tea fungus. Both types of yarrow kombucha showed good
330 antimicrobial and antioxidant activity. Yarrow infusion kombucha showed antiproliferative
331 activity against cells of human rhabdomyosarcoma and human cervix carcinoma Hep2c
332 (HeLa) (Vitas et al., 2018).

333 The beverage obtained from ten-day tea fungus fermentation of a ginger infusion
334 possessed ginger bioactive components e.g. 6-gingerol and 6-shogaol, which have anti-
335 inflammatory and antitumor activity leading to the inhibition of tumour proliferation and
336 stimulation of its apoptosis. The fermented ginger infusion decreased catalase, glutathione
337 and malondialdehyde activity in tumour homogenate (Salafzoon, Mahmoodzadeh Hosseini,
338 & Halabian, 2018).

339 *Leaves*

340 Rooibos tea does not contain catechins, so kombucha made from rooibos has a lower
341 antioxidant activity than kombucha made from green or black tea. However, rooibos
342 kombucha has a glucuronic acid amount comparable to kombucha made from black tea and
343 contains other valuable compounds, e.g. rutin, aspalathin, orientin and isoorientin, all with
344 antioxidant activity. Rooibos kombucha showed a significant positive effect on the recovery
345 of H₂O₂ induced oxidative damage of fibroblast cell lines (Gaggia et al., 2018).



346 Guava (*Psidium guajava*) is an evergreen shrub native to South and Central America
347 and the Caribbean. Its leaves, after drying, are used in the traditional medicine: as an anti-
348 inflammatory, hypoglycemic, antidiarrheal, antioxidant and antibacterial agent. During tea
349 fungus fermentation of guava leave extracts, new products with a completely different
350 composition and potential health-promoting effect than tea kombucha are created (Moreno-
351 Jiménez et al., 2018). It was shown that the primary polyphenol in guava leaves is quercetin
352 with lower concentrations of other flavonoids, e.g. kaempferol (Alnaqeeb et al., 2019;
353 Metwally, Omar, Ghazy, Harraz, & El Sohafy, 2011). The content of flavan-3-ols (catechin,
354 gallic acid and epicatechin) in guava kombucha was lower than in tea kombucha, but
355 unlike the tea beverage, the concentration of these compounds increased with the time of
356 fermentation. Tea polyphenols are pH-sensitive: they are more stable in an acidic pH. The
357 maximum amount of organic acids in tea kombucha was observed on the fifth day of
358 fermentation, while in guava kombucha the maximum concentration of organic acids is
359 reached after nine days of fermentation. The different time for formation of organic acids
360 results in differences in pH and, as a result, influences the profile of polyphenols (Zeng, Ma,
361 Li, & Luo, 2017).

362 Fermentation of sweetened infusion of oak leaves (*Quercus* spp.) by tea fungus
363 changes its sensory properties. This is due to the microbiological degradation of compounds
364 present in unfermented beverages, which cause its tartness and bitter taste (e.g. flavan-3-ols,
365 hydroxybenzoic acid derivatives and hydroxycinnamic acids). The microbial modification of
366 these compounds leads to an increase in beverage sensory acceptability. The content of other
367 polyphenols in oak leaf kombucha e.g.: benzoic acid, vanillic acid, gallic acid, caffeic acid, 4-
368 hydroxybenzaldehyde, 2-hydroxybenzoic acid, 4-hydroxy-phenylethanol, and coumaric acid
369 was higher than in the infusion of unfermented oak leaves. In the case of gallic acid, its
370 concentration in the fermented oak leaf beverage was similar to the amount in black tea

371 kombucha. The presence of quercetin glucuronide in oak leaf kombucha is also responsible
372 for its antioxidant properties and anti-inflammatory activity. Fermented oak leaf beverages
373 reduce the nitric oxide production (NO) in macrophages stimulated with lipopolysaccharide
374 (LPS) – a major element of the outer membrane of gram-negative bacteria. Macrophages
375 stimulated with LPS produce proinflammatory cytokines, prostaglandins and high levels of
376 free radicals, such as NO (Fujihara et al., 2003). NO destroys phagocytosed cells and is
377 involved in the host immune response. Its production is associated with the induction of
378 inflammation. This compound is unstable and in the presence of superoxide anions may form
379 toxic peroxynitrite, causing oxidative damage. Oak leaf kombucha treatment reduced the
380 production of NO to a similar level to that obtained by macrophages without LPS stimulation
381 (Vázquez-Cabral et al., 2017, 2014).

382 *Fruits*

383 Salak is a fruit growing in a palm from the *Arecaceae* family in Indonesia. It is
384 commonly called “snake fruit” due to its brown, scaly skin. Beverages obtained as a result of
385 a 14-days of tea fungus fermentation of the salak juice displayed anti-hyperglycaemic
386 activity. It was shown that 28-day oral administration of salak kombucha for diabetic rats
387 (doses 5-15 mL/kg body weight/day) caused a significant glucose reduction in blood plasma
388 (31-59%) (Zubaidah et al., 2018b). According to the authors, this is due to the high content of
389 antioxidants, such as tannins, polyphenols and organic acids, such as acetic, citric and lactic,
390 which can decrease the fasting plasma glucose level by increasing the glucose uptake of cells.
391 Additionally, salak kombucha enhances superoxide dismutase (SOD) activity and decreases
392 malondialdehyde (MDA) level in blood serum. Probably, the flavonoid compounds present in
393 kombucha are responsible for increasing the SOD activity by indirectly influencing on the
394 synthesis of SOD in cells (Zubaidah et al., 2018b; Zubaidah et al., 2019). Zubaidah et al.,
395 (2018a) also showed that consumption of kombucha from salak juice by rats resulted in the



396 regeneration of their pancreatic β -cells. The salak kombucha was more effective in treating
397 streptozotocin-induced diabetes than kombucha from black tea, due to the differences in total
398 phenolics and acids content. Salak kombucha's activity in lowering fasting plasma glucose
399 levels, reducing oxidative stress and lipid profiles was comparable to the activity of
400 metformin, what indicates that salak kombucha could potentially replace this drug in diabetes
401 therapy (Zubaidah et al., 2018a).

402 *Vegetables*

403 Vegetables fermented by tea fungus can be used to produce products with bioactive
404 components. It has been shown that after 14 days of tea fungus fermentation of blanched
405 spinach pulp, the total polyphenol content increases about 93% (Aspiyanto et al., 2016).
406 Fermented spinach pulp had a significantly higher content of folic acid than the raw
407 vegetable. The freeze-dried fermented spinach pulp of spinach could be a good source of
408 folates. Such dry products could be used as functional food additives (Nugraha, Susilowati,
409 Aspiyanto, Lotulung, & Maryati, 2017).

410 *Juices*

411 Tea fungus fermentation of pasteurized juices from pomegranate, red grape, sour
412 cherry and apple allowed kombucha vinegar (4% of acetic acid) to be obtained. During
413 fermentation process of all juices, there were similar physicochemical changes: significantly
414 increasing of acids and fructose concentration, lowering the pH and content of alcohol and
415 sucrose. The lowest concentration of acetic acid was noted in fermented apple juice, while the
416 highest in fermented pomegranate juice. The raw material for fermentation determines the
417 flavor of the product (Akbarirad, Assadi, Pourahmad, & Khaneghah, 2017). Fermentation of
418 the juices from pomegranate and sour cherry also leads to the tea fungus producing
419 considerable amounts of glucuronic acid, 17.07 and 132.5 g/l, respectively. Kombucha from



420 fruit juices may be a component of a diet supplementing the intake of this important
421 compound (Yavari, Assadi, Moghadam, & Larijani, 2010; Yavari et al., 2017).

422 *By-products and wastes*

423 Soybean whey is a by-product of soy processing, which contains a lot of valuable
424 substances, such as proteins, oligosaccharides, isoflavones, organic acids and minerals.
425 Beverages obtained from soybean whey during six days of fermentation had fruity and floral
426 flavors from nonanal and undecanal aldehydes formed by microorganisms. It was shown that
427 these products had higher antioxidant activity than unfermented soy whey and antibacterial
428 activity against *Staphylococcus aureus*, *Bacillus subtilis* and *Escherichia coli* (Tu, Tang, Azi,
429 Hu, & Dong, 2019).

430 Another example of an interesting fermented product is obtained from banana peel
431 extract. It is characterized by a new taste, smell and color. In comparison with traditional tea
432 kombucha, beverages from banana peels extracts have a lower pH and higher phenolic
433 content than unfermented extracts. Final products showed significant antioxidant activity,
434 which may result from the microbial fermentation of the protein in banana peels (Pure &
435 Pure, 2016).

436 *Milk*

437 Tea fungus can be used for the preparation of fermented milk products without or with
438 additives, such as transglutaminase, whey concentrates or extracts from other plants. During
439 fermentation, substances with health-promoting effects are formed from milk compounds,
440 e.g. peptides with the ability to inhibit an angiotensin-converting enzyme (ACE), which
441 causes elevated blood pressure and congestive heart failure. Synthetic drugs for hypertension,
442 such as captopril have many side effects, so bioactive peptides delivered naturally during
443 food fermentation arouse much interest. Moreover, rats fed with fermented milk products had
444 low harmful LDL cholesterol, glucose and aminotransferases in the blood (Al-Dulaimi, Abd-



445 Alwahab, & Hasan, 2018; Elkhtab, El-Alfy, Shenana, Mohamed, & Yousef, 2017; Iličić et
446 al., 2017; Iličić, Milanović, Kanurić, Vukić, & Vukić, 2016; Kanurić et al., 2018).

447 **4. Cellulose synthesis by Kombucha culture**

448 Bacterial cellulose (BC) is an extracellular metabolite of many bacterial species
449 (Picheth et al., 2017). This is a biopolymer with exceptional material properties, e.g. lack of
450 impurities like pectin, lignin or hemicellulose, high tensile strength and great water-uptake
451 capacity (Ullah, Santos, & Khan, 2016). The pathway of cellulose biosynthesis in bacteria is
452 complex and consists of several stages. The substrates in biosynthesis may be glucose,
453 fructose, ethanol, acetic acid, citric acid, or glycerol. Enzymatic transformations lead to the
454 formation of cellulose fibrils that combine with each other to form chains, then microfibrils
455 and finally a 3-D structure of about 1,000 separate glucan chains. BC has an excellent water
456 capacity – it can hold up to 200 times more water than its dry mass (Semjonovs et al., 2017;
457 Villarreal-Soto et al., 2018). BC thermal stability arises from its high crystallinity. This
458 property allows for sterilization of BC at 121°C and that causes it to have superiority over
459 other polymers that typically change their properties above 100°C [Cacicedo et al. 2016].

460 BC can be produced by both gram-negative and gram-positive bacteria, such as
461 *Aerobacter* sp., *Agrobacterium* sp., *Achromobacter* sp., *Aerobacter* sp., *Azotobacter* sp.,
462 *Rhizobium* sp., *Sarcina* sp., *Salmonella* sp., *Pseudomonas* sp. and *Gluconacetobacter* sp..
463 Bacteria from the genus *Komagataeibacter* (family *Acetobacteraceae*) are usually used for
464 the industrial production of BC, especially *K. xylinus* (formerly *Gluconacetobacter xylinus*)
465 (Mohammadkazemi, Azin, & Ashori, 2015; Villarreal-Soto et al., 2018). The enzymatic
466 activity of *Komagataeibacter* leads to the synthesis of uridine diphosphoglucose, which is a
467 precursor of cellulose, then the single cell can polymerize up to 200,000 glucose residues per
468 second with β -1,4-glycosidic bonds, so the yield of cellulose is highly effective. This may be
469 due to the presence of a CcpA protein called “cellulose complementing factor.” It is encoded



470 only in the *Komagataeibacter* genus and may be responsible for its high activity in the
471 synthesis of cellulose (Römling & Galperin, 2015).

472 BC is produced extracellularly in the form of fibrils attached to the cells. When the
473 culture is static at the air-liquid interface, one floating biofilm is formed. However, when the
474 culture is agitated (e.g. by continuous mixing) irregular masses of fibrillar structures are
475 distributed in the medium (Neera, Ramana, & Batra, 2015). BC is a mechanical protection for
476 the cells and by retaining them on the surface of the fermented liquid ensures oxygen for the
477 bacteria. Additionally, it is assumed that BC can form a reticulation in which nutrients move
478 by diffusion, so bacteria located deep inside the structure have access to them (Iguchi,
479 Yamanaka, & Budhiono, 2000).

480 BC can be successfully used as an emulsion stabilizer, thickener and source of dietary
481 fiber in the diet. It has higher activity in lowering serum triglycerides, LDL and total
482 cholesterol as well as liver total lipids and liver total cholesterol than plant cellulose. BC
483 could be used as a promising low-calorie food ingredient for different applications e.g. as
484 dietetic snacks (Chau, Yang, Yu, & Yen, 2008). Additionally, it can be used in the cosmetic
485 industry as a facial mask, scrubs, cleansing formulation and, due to its biocompatibility,
486 permeability to liquid and gases and transparency, as a material for contact lenses. In
487 addition, BC is applied in medicine. It is successfully used as a material for wounds
488 dressings, burn treatments and as a drug delivery systems. Tests on animals have shown the
489 possibility of using BC as cardiovascular implants (Kończowska et al., 2019). Additionally,
490 it can be used as artificial blood vessels, cartilage, bones, skin and as a wound healing
491 scaffold for the tympanic membrane (Cacicedo et al., 2016; de Oliveira Barud et al., 2016;
492 Ullah et al., 2016).

493 Despite its advantages, unique properties and comprehensiveness of applications, BC
494 is rarely produced because of its price. Bacteria are grown on complex media, with the

495 addition of ethanol, which improves cellulose yield up to four times (Islam, Ullah, Khan,
496 Shah, & Park, 2017). Methods leading to cheaper and more efficient BC production are being
497 sought and alternative media such as fruit juices or waste are being tested. The addition of
498 apple juice into the static culture of a Hestrin–Schramm medium inoculated with *K. rhaeticus*
499 P 1463 isolated from kombucha allowed the production of cellulose with a high yield.
500 Prolonged fermentation for 14 days and gradual supplementation of the carbon substrate led
501 to a cellulose yield of about 9.5 g/L. The obtained biomaterial has good physical and
502 mechanical properties (Semjonovs et al., 2017). A similar yield of cellulose (about 9.1 g/L)
503 was obtained in diluted pineapple juice using the *K. xylinus* strain DFBT (Neera et al., 2015).

504 The carbon source also is a crucial factor for affecting the properties of bacterial
505 cellulose. The addition of mannitol to the Hestrin–Schramm medium leads to the most
506 efficient BC production by *K. xylinus*, whereas food-grade sucrose and date syrup the yield of
507 cellulose is not satisfactory (Mohammadkazemi et al., 2015). However, another study proves
508 that sucrose as a carbon source for a strain of *K. xylinus* DFBT – results in a high yield of BC
509 (Neera et al., 2015).

510 Fermentation of sweetened black tea using the tea fungus also leads to the production
511 of BC with high efficiency (Al-Kalifawi, 2014). Our preliminary studies showed that BC
512 obtained during the fermentation of chokeberry pomace extracts by tea fungus exerts high
513 antioxidant and antimicrobial activity (unpublished data). Such cellulose can be used in many
514 ways, for example as a functional food additive, as dietary fiber with antioxidant and
515 antimicrobial properties, or as an active packaging material. The possibility of using BC
516 obtained on media with a high antioxidant potential must be confirmed in studies. In the
517 available literature (to the best of our knowledge), there is very little data on the properties of
518 BC obtained during the production of kombucha beverages Zhu, Li, Zhou, Lin, & Zhang
519 (2014) showed that BC obtained by the tea fungus fermentation of black tea had



520 biocompatibility with Schwann cells and did not exert hematological and histological toxic
521 effects on nerve tissues.

522 **5. Conclusion and perspectives**

523 The health benefits of drinking fermented tea, such as its antioxidant and anti-
524 inflammatory activity, the ability to reduce LDL cholesterol and blood glucose, and its
525 hepatoprotective properties cause the drink to be very popular. However, more research
526 should be performed to fill in an existing gap in the direct evidence about the functionality of
527 kombucha products. It is a necessary to determine the various factors affecting the functional
528 features of kombucha and its safety.

529 The idea to use tea fungus for the fermentation of alternative raw materials arises from
530 the unique properties of tea kombucha and the desire to obtain an edible product with unusual
531 functional properties e.g. with the content of uncommon pro-health substances or with an
532 increased amount of biologically active compounds i.e. polyphenols. Additionally, tea fungus
533 fermentation may release bioactive components from raw materials into the fermentation
534 liquid, which allows a product with a high biological value and an enriched composition to be
535 obtained. There is still a large number of potential raw materials that have not been tested in
536 terms of suitability for the production of a functional, fermented product, such as fruit
537 pomace. Pomaces are a result of processing fruits and vegetables and are usually treated as
538 waste. They constitute 10–35% of the mass of raw material and contain many valuable
539 substances, such as vitamins, polyphenols, minerals or fiber, so they should be treated as an
540 intermediate product for further processing e.g. by fermentation by tea fungus. Such
541 processes may lead to new products with health-promoting properties. Our preliminary
542 research indicates that tea fungus effectively ferments extracts from fruit pomaces, leading to
543 the creation of beverages with interesting sensory and functional properties (data
544 unpublished). Properties of new fermented beverages should also be tested depending on the



545 starter cultures used or the fermentation time (Amarasinghe, Weerakkody, & Waisundara,
546 2018; Gaggia et al., 2018; Ii & Kumar, 2016; Vázquez-Cabral et al., 2014).

547 The large microbial diversity of kombucha and the complex interactions between
548 microorganisms make it challenging to investigate and understand the functioning of this
549 unique ecosystem. However, understanding the interactions between microorganisms,
550 determining the relationships between them and gaining knowledge about how they create
551 specific niches closely associated with each other, would allow for the selection of
552 appropriate media, optimal fermentation conditions, and directing the fermentation process.
553 This would favour increasing the biosynthesis efficiency of the desired bioactive compounds
554 in kombucha.

555 **Declaration of interest**

556 The authors declare no corporate/business, funding or founder sponsor conflict of interest.

557

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