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Review on tannins: Extraction processes, applications and possibilities

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A B S T R A C T S

Tannins are found in most of the species throughout the plant kingdom, where their functions are to protect the plant against predation and might help in regulating the plant growth. There are two major groups of tannins, i.e., hydrolyzable and condensed tannins. The tannins are being used as important and effective chemicals for the tanning of animal hides in the leather processing industry since the beginning of the industry. Additionally, the tannins have been using as mineral absorption and protein precipitation purposes since 1960s. These are also used for iron gall ink production, adhesive production in wood-based industry, anticorrosive chemical production, uranium recovering chemical from seawater, and removal of mercury and methylmercury from solution. Presently, tannins are considering as bioactive compound in nutrition science. It has also been considered for advanced applications, i.e., 3D printing and biomedical devices. The application of tannins as medicine is another new dimension in medical science. This paper outlines the general information about tannins followed by their extraction process. The utilization of tannins has also been presented in a broader scale. Depending on all these information, the article also describes the impending utilization of tannins for ensuring high-sustainability and better environmental performance.

1. Introduction

The word "tannin" originates from the ancient Celtic word for oak and was introduced by Seguin to explain the ability to convert hide or skin into leather by a plant extract in 1796 (Hagerman, 2002). Generally, tannins are obtained from natural renewable resources, i.e., plants (Pizzi, 2008; Ramakrishnan and Krishnan, 1994) which are the secondary phenolic compounds of plants (Hagerman, 2002; Sharma, 2019). More specifically, tannins are either galloyl esters or oligomeric and polymeric proanthocyanidins (Khanbabaee and van Ree, 2001) produced by the secondary metabolism of plants (Hagerman, 2002; Lewis and Yamamoto, 1989), i.e., synthesized by biogenetic pathways (Lewis and Yamamoto, 1989). Proanthocyanidins are the results of polyketide (malonyl-CoA) and phenylpropanoid metabolism and gallic acids are formed from shikimate directly (Lewis and Yamamoto, 1989). Tannins are the main polyphenolic secondary metabolites distributed widely in the range of 5 to 10% of dry vascular plant materials (Barbehenn and Constabel, 2011) found mainly in bark, stems, seeds, roots, buds, and leaves (Barbehenn and Constabel, 2011; Giovando et al., 2019; Tomak and Gonultas, 2018). Tannins are also available in foodstuffs, i.e., grapes, blackberries, strawberries, walnuts, cashew nuts, hazelnuts, mangoes and tea (Clifford and Scalbert, 2000). Tannins act as plant defensive agents, protect trees from fungi, pathogens, insects and herbivorous animals (De Bruyne et al., 1999; Hagerman et al., 1998; Khanbabaee and van Ree, 2001; Sharma, 2019).

Broadly, tannins are categorized into two main groups, i.e., condensed tannins and hydrolyzable tannins. Condensed tannins are composed of flavonoids (flavan 3-ol or flavan 3, 4-diol) without a sugar core, however, the hydrolyzable tannins are composed of ellagic and gallic acids with a sugar core mainly glucose (Khanbabaee and van Ree, 2001; Sharma, 2019). Among the different types of tannins, hydrolyzable tannins have limited sources in the nature compared to condensed tannins (Haslam, 1982; Hillis, 1985). Thus, condensed tannins are dominating the world market consisting more than 90% of the total commercial tannins (Filgueira et al., 2017; Pizzi, 2008). According to Pizzi (2006), the total annual extraction of tannin was 200,000 t worldwide of which 90% was condensed tannins. Tannins are extracted with water alone or by mixing with other solvents like methanol, ethanol, acetone, NaOH. The solid to solvent ratio and the extraction temperature are very important for the extraction of tannins (Arinaa and Harisuna, 2019; Dentinho et al., 2020; Duraisamy et al., 2020; Luo et al., 2019; Martins et al., 2020; Naima et al., 2015; Poaty et al., 2010; Rhazi et al., 2019). Alongside, the particle size also

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influences the extraction process. Antwi-Boasiako and Animapauh (2012) reported that hot water extraction process provided better results. However, according to Duraisamy et al. (2020) and Medini et al. (2014), the extraction was better when methanol-water solvent was used.

Tannins are mainly used by the leather industry for both hide treatment and the color of leather since past centuries (Kemppainen et al., 2014; Pizzi, 2008). However, the phenolic structure of tannins has the potentiality to use in other applications like adhesives for wood industry (Pizzi, 2006), insulating foams (Tondi et al., 2009), mineral industry, wine production industry, animal nutrition, oil industry (Pizzi, 2006), water treatment plant (Combs, 2016) and protecting metal from corrosion (Luo et al., 2019; Ostovari et al., 2009). The extracted tannins can also be used as adhesive, biocide and fungicide, which could open a new dimension for the wood-based industry (Ogunwusi, 2013). It has also the potentiality to make proteins and other polymers like pectin (Ramakrishnan and Krishnan, 1994) apace with the use in medical science (Ogawa et al., 2018; Ogawa and Yazaki, 2018). All these applications make tannins an important green biochemical which attracts researchers nowadays (Carrieri et al., 2016; Combs, 2016; Ghahri and Pizzi, 2018; Nath et al., 2018; Ogawa et al., 2018; Shirmohammadli et al., 2018).

Researchers are substantially working on the extraction and application of tannins (Arinaa and Harisuna, 2019; Chen et al., 2020a, 2020b; Liao et al., 2020; Martins et al., 2020; Naima et al., 2015; Poaty et al., 2010; Zhang et al., 2019). Depending on those studies, there are some comprehensive reviews which deals mainly with the structure and role of tannins on animal and human health (Bele et al., 2010; Bernhoft, 2010; Chung et al., 1998; Clauss, 2003; Feng et al., 2013; Hassanpour et al., 2011; Kraus et al., 2003; Rowe and Conner, 1979; Schofield et al., 2001; Serrano et al., 2009; Versari et al., 2013). However, there is no extensive review particularly on the extraction of tannins with its applications. Thus, this review paper aims to provide a wide-ranging insight into the topic including the extraction process, current uses and the potential applications of tannins.

2. Tannins

The term tannin is widely applied to a complex large biomolecules of polyphenolic nature having sufficient hydroxyls and other suitable groups such as carboxyls to form strong complexes with various macromolecules (Fig. 1). They are commonly found in both gymnosperms and angiosperms and are categorized as condensed and hydrolyzable tannins (Khanbabaee and van Ree, 2001; Navarrete et al., 2013; Saad et al., 2014). The hydrolyzable tannins contain glucose or other polyhydric alcohols esterified with gallic acid (gallotannins) or hexahydroxydiphenic acid (ellagitannins) (Hobbs, 2008; Kemppainen et al., 2014). Depending on the esterification, hydrolyzable tannins are subdivided into gallotannins and ellagitannins (Khanbabaee and van Ree, 2001). Acid hydrolysis of hydrolyzable tannins helps to get gallic acid, ellagic acid or other similar species (Haslam, 2005). On the other hand, condensed tannins are composed of flavolans or polymers of flavan-3-ols (catechins) and/or flavan 3:4-diols (leucoanthocyanidins) (Hillis, 1997; Kemppainen et al., 2014). Compare to the hydrolyzable tannins, condensed tannins have a wide range of molecular weight ranging from 500 to over 20,000 (Haslam and Cai, 1994; Jiang et al., 2002), and have the ability to react with aldehydes to generate polymeric materials (Jiang et al., 2002). Phlobaphene, a water insoluble product, is possible to produce by polymerization of condensed tannins. Char, an important wood-based product, yield is higher in condensed tannins compared to hydrolyzable tannins as it has condensed structure (Sebestyen et al., 2019). The tannins are widely distributed in many species of plants. Plant species that contain higher amount of condensed tannins are wattle, quebracho, mangrove and hemlock, whereas chestnut and myrobalan species contain higher amount of hydrolyzable tannins (Hillis, 1997).

3. Extraction of tannins

Tannins have attracted significant attention because of its variety of potential applications, and have considerable abundance in nature. However, its amount in plant depends on the geography, biological origin, species, populations, age and position in the tree, i.e., inner or outer wood of trees (Pizzi and Cameron, 1986; Puech et al., 1999). Considering the potential applications, tannin-related researches have undergone a great boost; however, due to tannins heterogeneous nature, the extraction process remains as the main challenges for their valorization. The extraction of tannins is not done in a single protocol, and the procedures are widely variable. Because of the extraction process, the extracted tannin contains different types of impurities including minerals, stilbenes and sugars (Bimakr et al., 2011; Kemppainen et al., 2014). For instance, the presence of carbohydrate in tannins reduce its anti-fungal efficacy (Anttila et al., 2013; Hmidani et al., 2019) as well as create problems during impregnation into wood for preservation (Anttila et al., 2013; Yalcin and Ceylan, 2017). Additionally, the amount of impurities depends on the processing parameters like particle size, temperature, pressure, time, solvent type, and solid to solvent ratio. Bello et al. (2020), Bimakr et al. (2011) and Hmidani et al. (2019) reported that temperature and solid to solvent ratio controlled the carbohydrate content in the extracted tannins. Hence, the extraction of tannins should be done carefully by controlling the operation parameters precisely.

In general, tannins are extracted either by hot water or water along with other solvents from the plant materials, i.e., bark, wood,

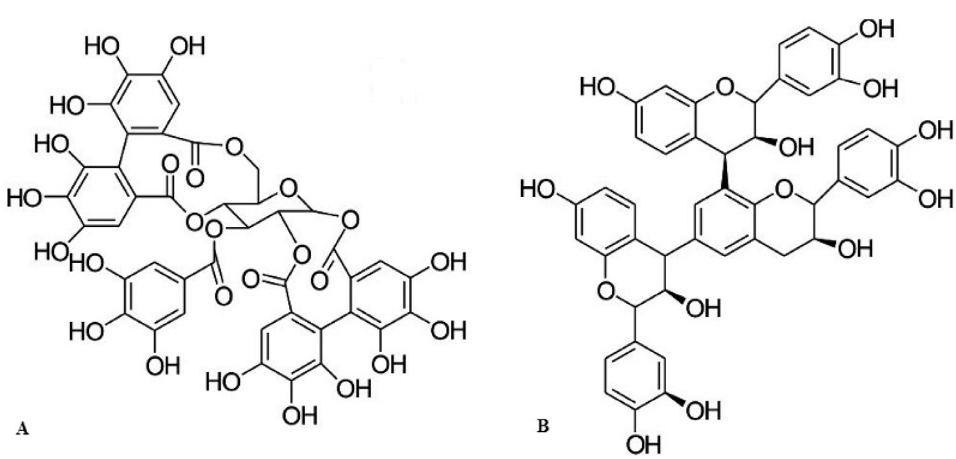

Fig. 1. Structure of (A) hydrolyzable and (B) condensed tannins (Raja et al., 2014).

stem, leaf. Acetone (Baaka et al., 2017; Bimakr et al., 2011; Dentinho et al., 2020; Hmidani et al., 2019; Kotze and Eloff, 2002; Meng et al., 2019; Poaty et al., 2010; Scalbert et al., 1989; Wurger et al., 2014), disopropyl ether, ethyl acetate, ethyl ether (Kotze and Eloff, 2002), methanol (Case et al., 2014; Romero et al., 2020), ethanol ((Naima et al., 2015; Rhazi et al., 2019), sodium sulphite (Poaty et al., 2010) and NaOH (Antwi-Boasiako and Animapauh, 2012; Guo et al., 2020) were used by different researchers as solvent with or without water. Dentinho et al. (2020) used acetone to extract tannins from dried leaves and green stems of rockrose (*Cistus ladanifer*), whereas 75% methanol with water was used to extract tannins from pine (*Pinus radiata*) barks (Case et al., 2014; Romero et al., 2020). In other studies, 50 to 80% methanol was used to extract tannin from fever tree (*Acacia xanthophloea*) (Duraisamy et al., 2020) and marsh rosemary (*Limonium delicatulum*) (Medini et al., 2014). Naima et al. (2015) and Rhazi et al. (2019) used different method to extract tannin from black wattle (*Acacia mollissima*) barks called microwave technology where water, 80% methanol and 80% ethanol were used for infusion and maceration. Besides, methanol (60%) was also used with ultrasound technology to extract tannins from acorn (Luo et al., 2019). The authors of those studies reported that methanol extraction provided more yield compared to the water extraction (Duraisamy et al., 2020; Medini et al., 2014)(Medini et al., 2014; Duraisamy et al., 2020). NaOH was also used for tannin extraction from mussoorie berry (*Coriaria nepalensis*) and 0.22% concentration among the different NaOH concentrations showed the best results (Gou et al., 2020). n-hexane has also been used to extract tannins, however, the yield is the lowest, thus, it is not at all a popular method of extraction (de Hoyos-Martinez et al., 2019). Addition of additives like enzymes, acids with solvent positively influence the quality and amount of tannins. According to a study, it was observed that the addition of enzyme in the solvent enhanced the tannins contents in the solution (Gao et al., 2019; Osete-Alcaraz et al., 2020). The authors used poly galacturonase and pectin-lyase with grape skin for tannin extraction. Enzymes can degrade the cell wall and cause pore formation, and thus, the release of tannins from grape skin can be increased (Arnous and Meyer, 2010; Li et al., 2006; Osete-Alcaraz et al., 2020; Pinelo et al., 2006). Similarly, 0.01% ascorbic acid with 70% acetone also positively influenced the extraction of total tannins, condensed tannins and phlorotannins from microalgae (Petchidurai et al., 2019). However, among the different methods, hot water extraction method is still popular and commonly used for the extractions of tannins in the industry (Fraga-Corral et al., 2020; Kemppainen et al., 2014) as well as in the laboratory (Tascioglu et al., 2013). The simplicity of the method and its lower cost are the main reasons for its popularity. Moreover, some of the researchers even reported that the amount of extracted condensed and hydrolyzable tannins were the highest when the solvent was hot water (Antwi-Boasiako and Animapauh, 2012). This might be related with the processing parameters of tannins extraction like species, types of raw materials, particle size, temperature and time. Types of solvent and its temperature also influence the extraction, which might have impact on the total volume of extraction. However, the temperature varies depending on the raw materials, process of extraction, time and particle size.

Bello et al. (2020) extracted tannin from spruce (*Picea abies*) barks by hot water method having the temperature of 85 °C, however, it was 90 °C when condensed tannins was extracted from pine (*Pinus radiate*) barks (Hussain et al., 2020). Depending on the solvent type, this temperature can be as high as 120 °C. Even with water as solvent, higher temperature (105 °C) was used when tannins were extracted from red angico (*Anadenanthera macrocarpa*), jabuticaba (*Myrciaria jabuticaba*) and umbu (*Spondias tuberosa*) barks (Martins et al., 2020). On the other hand, the optimum temperature was 75 °C when tannins were extracted from galls of manjakani (*Quercus infectoria*) (Arinaa and Harisuna, 2019). It was obsreved that the use of water as the solvent for extraction required lower temperature (Duraisamy et al., 2020). When methonaol/ethanol was used with water as sovents, the temperature ranged between 60 and 120 °C (Case et al., 2014; Romero et al., 2020), however, higher temperature showed better results. In case of NaOH as solvent, the best temperature was 82 °C for the extraction of tannins from bark (Naima et al., 2015; Rhazi et al., 2019). This processing temperature was lower (room temperature to 60 °C) when the acetone was used as solvent for the extraction of tannins (Dentinho et al., 2020; Luo et al., 2019). Pressure application helps to extract tannins at lower temperature (Bianchi et al., 2014b) as well as the advance technologies like ultrashound, microwave technology remain lower processing temperature (Luo et al., 2019; Naima et al., 2015; Rhazi et al., 2019). However, the size of the particles play a significant role in the extraction process.

For efficient extraction, these plant parts are grounded prior to any type of extraction (Antwi-Boasiako and Animapauh, 2012; de Hoyos-Martinez et al., 2019). However, the particle size varies depending on other parameters like efficacy level, time, temperature, solvent type, raw materials type, and process. Antwi-Boasiako and Animapauh (2012) used barks and wood chips to extract tannins from it having the particle size of 0.5 μm and 0.5–5 mm, respectively. Different researchers extracted tannins from different plants by using different solvents where they used different particle sizes as illustrated in Table 1. Tannins extraction is quicker when the particle size is smaller (Case et al., 2014; Luo et al., 2019; Romero et al., 2020) because solvents penetrates in to the particle easily which shorten the extraction time.

Besides the aforementioned tannin extraction techniques, there are many other advanced techniques including super critical, ionic liquid assisted microwave, infrared-assisted and pressurized hot water extraction technique. In the pressurized water extraction method, 374 °C temperature and 22.1 MPa pressure are used (de Hoyos-Martinez et al., 2019; Ersan et al., 2018). Ionic liquids, i.e., 1-ethyl-3-methylimidazolium Br, 1-butyl-3-methylimidazolium Br, 1-hexyl-3-methylimidazolium Br, 1-octyl-3-methylimidazolium Br, 1-decyl-3-methylimidazolium Br, 1-butyl-3-methylimidazolium Cl, 1-butyl-3-methylimidazolium BF_4, 1-butyl-3-methylimidazolium NO_3, and 1-butyl-3-methylimidazolium OH have been used as a pretreatment prior to microwave extraction (Yang et al., 2012). In infrared-technique, infrared lam is used to heat during extraction. The efficiency of this method depends on the wavelength of the infrared heater, distance between source of infrared and material, and the solvent (Cai et al., 2011; Chen et al., 2010; Escobedo et al., 2016). Extraction of tannins by gamma radiation has also been studied. For this technique, specific solvents are required to soak the material. On the other hand, materials and solvents can be irradiated by gamma radiation as well (Santos et al., 2011). Supercritical is another modern technology for extracting tannins where supercritical solvents, i.e., carbon dioxide, butane, pentane, fluorinated hydrocarbons, sulfur hexafluoride and nitrous oxide are used. Co-solvent or modifier is used to improve the selectivity of CO_2 (Ashraf-Khorassani and Taylor, 2004; de Hoyos-Martinez et al., 2019; Ersan et al., 2018; Talmaciu et al., 2016; Wang and Weller, 2006; Yepez et al., 2002).

The extraction efficiency and the quality of tannins depend on the duration of the extraction (Hussain et al., 2020; Luo et al., 2019), i.e., long extrction durtion yields higher amount of tannins. The cell structure of plant is destroyed with time in the solvents, and the yield of tannin extraction is increased (Petchidurai et al., 2019), however, quality might decrease with time. Solvent-to-solid ratio is another important factor which governs the tannins extraction process (Dentinho et al., 2020; Gou et al., 2020). Continuous mixing of solvents with the particles also helps the extractioin process, and better mixing is possible when there is higher solvent-to-solid ratio. However,

Table 1
Different types of extraction methods practiced to extract tannins from different species using different types of solvents.

Extraction Methods					Raw material			References
Solvent type	Equipment	Process parameters			Part	Species	Size	
		Temp. (°C)	Time (hours)	Others				
Acetone-water	Soxhelt and rotating shaker	50	10	3 h shaking at 120 rpm	Bark	Bay berry	–	Petchidurai et al. (2019);
	Rotating shaker	28 -30	10		Whole part	Brown, green and red algae	–	Meng et al. (2019)
	Rotating shaker and centrifuge	–	–	1 h shaking, centrifuge at 3200 rpm for 10 min	–	–	–	
	Bowl	Room	24	Wash (petroleum ether)	Sawdust	Oak	–	Poaty et al. (2010)
	Bowl, stirrer	Room	48	1:10 (solid to solvent), closed container, stirring	Leaves and stems	Rockrose	1 mm	Dentinho et al. (2020)
	Bowl, stirrer	60	2	Stirring at 150 rpm	Rice straw		<1 mm	Shi et al. (2020)
Acetone-ethanol	Bowl	–	24	–	Leaves	Guava	–	Mailoa et al. (2013)
Methanol-water	Ultrasound	–	0.04	Ultrasound with enzyme addition	Acorn	–	200–1000 μm	Luo et al. (2019)
	Magnetic stirrer	60	0.5	–	Shoot	Marsh rosemary	–	Medini et al. (2014)
	Batch reactor	120	2	1:5 (solid to solvent), 90 min for raising and 30 min to retain at 120 °C	Barks	Radiata pine	1.2 mm	Case et al. (2014); Romero et al. (2020)
Hot water	Accelerated Solvent Extractor	60	0.08	–	Barks	Norway spruce, Silver fir	3 mm	Bianchi et al. (2014a)
	Rotating pressure cooker	60, 75, 90	0.16 to 2	–	Barks	Norway Spruce	–	Kemppainen et al. (2014)
	Hot plate, magnetic stirrer	100	0.33	–	Barks, heartwood	Mimosa, quebracho, pine	Fine powder	Tascioglu et al. (2013)
	Bowl, stirrer	85	2	Stirring at 100 rpm	Barks	Norway spruce	–	Bello et al. (2020)
	Bowl	90	–	–	Barks	Radiata pine	–	Hussain et al. (2020)
	Bowl	105	6	Constant reflux	Barks	Red Angico, Jabuticaba and Umbu	–	Martins et al. (2020)
	Bowl	50, 75, 100	2	1:20 (solid to solvent)	Galls	Manjakani	–	Arinaa and Harisuna (2019)
Normal water	Bowl	Room	12	–	Pod	Babul	–	Mahdi et al. (2009)
Hot water and Methanol-water	Soxhlet	60, 90	4	–	Barks	Fever tree	–	Duraisamy et al. (2020)
Water-sodium sulphite	–	70	–	–	Heartwood	Quebracho	–	Poaty et al. (2010)
Water-NaOH	Reactor	120	2	1:8 (solid to solvent)	Pomace	Grape	–	Ping et al. (2011a)
Water-NaOH		70 to 90	0.67 to 1.33	1:15 to 1:25 (solid to solvent)	Barks	Masuri berry	<0.1 mm	Guo et al. (2020)
Hot water and Water-NaOH	Soxhlet	–	6	–	Barks	Pattern wood, aidan fruit and African wild rubber	0.5 μm	Antwi-Boasiako and Animapauh (2012)
Water, methanol-water, ethanol-water	Microwave	40, 60, 80 (infusion and maceration)	<2	1:20 (solid to solvent), 150 to 600 W	Barks	Black wattle	0.5 mm	Naima et al. (2015); Rhazi et al. (2019)

* (-) indicates that related information are not available in the respective literature.

this ratio modifies the particles but not for the solvent governing the extraction of tannins.

4. Applications of tannins

In a vascular plant, tannins are produced by a chloroplast-derived organelle and physically located in the vacuoles or surface wax of plants. These storage sites keep tannins active against plant predators, but also keep some tannins from affecting plant metabolism while the plant tissue is alive. Additionally, tannins are often found in the growth areas of trees, i.e., secondary phloem and xylem, the layer between the cortex and epidermis, thus, indicate its influences on the growth of these tissues. In general, amount of tannin is higher in the bark compared to the other parts of a tree, i.e., leaves, woods, shoots (Antwi-Boasiako and Animapauh, 2012). Tannins are also different in terms of their properties. This section discusses the types of tannins with its applications.

4.1. Applications of condensed tannins

Condensed tannins are widely used for various purposes. The complex interaction of tannins with protein brings a good potentiality to use in nutrition for animal health and its application for the industrial process (Cadahia et al., 1996). The applications of condensed tannins have been discussed in this section. The sources and applications of condensed tannins are presented in summarized form in Table 2.

4.1.1. Leather processing industry

In general, condensed tannins are the major component of the commercial tannins, which are used for tanning of leather in a tannery. The major contributors for the world's supply of condensed tannins are extracted from mangrove species, wattle and quebracho. Condensed tannins are selected based on their tanning quality, which is dependent on the chemical composition of condensed tannins for heavy leather production. Condensed tannins have high resistance to detannage (Lipsitz et al., 1949), thus, it is suitable for tanning of leather in the industry. Quebracho and wattle tannins are more resistant to concentrate urea solution in comparison to hydrolyzable tannins (Gustavson, 1947). Tannins react with the basic groups of protein in leather matrix (Covington, 1998; Das Gupta, 1987; Heidemann, 1993; Slabbert, 1998). At first, hydroxyl groups (OH) of tannins bind with the active collagen centers, and it is then continued to fill the interfibriller spaces in leather (Das Gupta, 1987). Tannins combine with the positively charged $-NH_3^+$ of collagen and eliminate the water. Therefore, it controls the bacterial growth for avoiding bad odor and makes stronger leather (Heidemann, 1993).

$$COO-.P.NH_3^+ + [Tannin]O^- + H+ \rightarrow COOH.P.NH_3^+ + [Tannin]O^-$$

$$COOH.P.NH_3^+ + [Tannin]O^- \rightarrow COOH.P.NH_3.[Tannin]O$$

Table 2
Sources and applications of condensed tannins studied by different researchers.

Types of application	Properties	Sources	References
Leather processing	Higher shrinkage temperature, resistance to detannage in leather industry	Babul, quebracho and wattle	Mahdi et al. (2009); Gustavson (1947); Lipsitz et al. (1949); Hathway (1962)
Fishing net Preservation	Bacterial and fungal resistant	Black cutch tree, Brazilian mahogany, spurred mangrove barks, red mangrove barks	Hathway (1962)
Plastic and Wood adhesive	Better strength properties of wood composites, better adhesive properties, superior water resistance properties	Quebracho, black wattle, maritime pine, bay berry, larch, grape, western hemlock, red cypress pine, Australian mangrove	Hathway (1962); Knowles and White (1954); Li et al. (2019b); Liu et al. (2020); Nico (1950); Cui et al. (2015); El Hage et al. (2011); Lei et al. (2008); Hafiz et al. (2020); Yang et al. (2019); Ping et al. (2011a); Ping et al. (2011b); Ping et al. (2012); Dalton (1950); MacLean and Gardner (1952); Hathway (1962); Janceva et al. (2011); Plomley et al. (1957); Pizzi (2008)
Oil and ceramics industry	Controlling viscosity of mud, and increase the suspending power of the casting slip	Quebracho	O'Flaherty et al. (1956); Hathway (1962)
Anticorrosive for metal	Protection against corrosion	Quebracho, black wattle, mangrove	Byrne et al. (2019); Byrne et al. (2020); Nardeli et al. (2019); O'Flaherty et al. (1956); Shah et al. (2011)
Wood preservation	Protection against fungus and termite, protection against of preservative	Black wattle, quebracho, and Turkish pine, valonia, chestnut, tara, and Oak	Tascioglu et al. (2012); Tascioglu et al. (2013); Tomak and Gonultas (2018); Thevenon et al. (2010)
Wood properties improvement	Improved dimensional stability of wood	Quebracho, black wattle, patula pine	Yalcin and Ceylan (2017); Bariska and Pizzi (1986)
Fire-resistance of wood	Improve fire resistance property	Black wattle	Tondi et al. (2012)
Water and waste water treatment plant	Higher coagulation efficiency, methylene blue and heavy metals absorbent	Norway spruce, wattle	Bello et al. (2020); Wang et al. (2019); Grenda et al. (2020); Grenda et al. (2018); Combs (2016); Wang et al. (2019)
Packaging	Anti-oxidant, UV-shielding	Quebracho	Li et al. (2019c)
Animal food	Nutritional	Red quebracho, rockrose, black wattle, chestnut	Costes-Thire et al. (2019a); Costes-Thire et al. (2019b); Dentinho et al. (2020); Lima et al. (2019); Aguerre et al. (2016); Aguerre et al. (2020)
3D printing	Good printing quality	Black wattle	Liao et al. (2020)

$$COOH.P.NH_3.[Tannin]O \rightarrow COOH.P.NH.[Tannin] + H_2O(Heidemann, 1993)$$

The binding of tannins with collagens is dependent on temperature, pH and molecular weight of tannins (Valls et al., 2009). Though tannin materials are dissimilar based on pH, salt content and natural conditions of acid content, these can be controlled maintaining proper conditions (Cheshire, 1946; Miekeley, 1935). pH of tan liquors is relatively high due to the absence of higher amount of phenolic acids in condensed tannins, and tannins are not carboxylated by themselves. Salt content of tannin materials varies depending mainly on the species and location, which contributes to the salt in tannin liquors. Mangrove plants tannins contain sodium chloride, whereas quebracho extracts possess sodium sulfate (Hathway, 1962). *Acacia nilotica* tannin with aluminum sulfate is used to produce leather, and this tannage has shown good cross-linking with collagens (Mahdi et al., 2009).

4.1.2. Preservation of fishing net

Preservation of fishing nets by various condensed tannins is popular in the Indo-Pacific countries. This process prevents the degradation of cellulose by bacterial and fungal cellulases. Fishing nets are submerged in hot tannin solution, and is repeated for several times for getting better preservation. Tannin-impregnated nets are further treated with either hot copper sulfate or dichromate solution for some cases (Atkins, 1936; Steven, 1950) for better stability of the tannins in net and its durability. The water solubility of tannin can be reduced by oxidation. Copper sulfate or dichromate solution can oxidize the tannins and fix them with net (Cecily and Kunjappan, 1971, 1973). Condensed tannin materials used as fishing net preservative are extracted from Burma cutch from *Acacia catechu* heartwood, Malayan (mangrove) cutch from *Carapa obovata* and *Ceriops candolleana* barks, and Borneo(mangrove) cutch from *Ceriops candolleana, Rhizophora candelaria*, and *Rhizophora mucronata* barks (Hathway, 1962).

4.1.3. Preparation of plastics and adhesives

Condensed tannins are phenolic raw materials, which react with formaldehyde and these can be used for the production of synthetic resins (Bianchi et al., 2014a; El Hage et al., 2011; Hafiz et al., 2020; Hathway, 1962; Lei et al., 2008; Yang et al., 2019). Nico (1950) studied the suitability of quebracho-formaldehyde resins for the production of adhesives and plastics. Molded plastics were produced by pressing the mixtures of quebracho and wattle tannins, paraformaldehyde, and plasticizer having the exact amount. The products satisfied all the required properties such as stability and water resistance as per the specifications of British Standards when phenol-formaldehyde was used (Hathway, 1962; Knowles and White, 1954). The hydroxyl groups of tannins can cross-linking with different compounds, i.e., formaldehyde for preparing adhesives and plastics (Hafiz et al., 2020; Santos et al., 2014; Wahab et al., 2014).

Many researchers have studied the applications of condensed tannins for the production of plywood and particle-board adhesives (Cui et al., 2015; Fechtal and Riedl, 1993; Ghahri and Pizzi, 2018; Hall et al., 1960; Heinrich et al., 1996; Herrick and Bock, 1958; Kim and Kim, 2004; Li et al., 2019b; Liu et al., 2020; Narayanamurti and Das, 1958; Narayanamurti et al., 1957; Nath et al., 2018; Pichelin et al., 2006; Pizzi, 2009, 1979, 1983; Plomley et al., 1976; Santos et al., 2017; Vazquez et al., 2012). Tannins help to make greater adhesion between fibers and matrix, and achieve better physical and mechanical properties of the wood-based composites (Hafiz et al., 2020; Tondi et al., 2012; Wahab et al., 2014). Sauget et al. (2013) used mimosa tannin as adhesive for the production of fiber biocomposites, and reported good physical and mechanical properties. However, adhesives prepared from *Tsuga heterophylla, Acacia mollissima* and *Callitris calcarata* barks showed less strength but higher water-resistance properties compared to the commercial adhesives (Dalton, 1950; MacLean and Gardner, 1952). Strong bondability and better water-resistant properties of adhesives for plywood were prepared by mixing paraformaldehyde, filler and sulfited tannin solutions obtained from *Eucalyptus crebra*, wattle extract and quebracho extract (Dalton, 1953; Knowles and White, 1954). Adhesives prepared from Australian mangrove tannins in addition with a small proportion of commercial phenol-formaldehyde, resorcinol-formaldehyde, or phenol- and resorcinol-formaldehyde complied with Australian and British standard for synthetic adhesives for plywood (Hathway, 1962; Janceva et al., 2011; Plomley et al., 1957). Adhesives for corrugated cardboard were also prepared from the extracted tannins of wattle (Pizzi, 2008). Researchers also produced novel adhesive by using polyethylenimine and condensed tannins which showed better water resistance properties having superior shear strength properties of wood composites (Li et al., 2004). Tannins obtained from *Acacia nilotica* along with formaldehyde had the ability to use as wood-based adhesives. The presence of B-ring of catechol *A. nilotica* tannins can increase the network formation, which enhances the strength properties of the composite (Osman, 2012).

4.1.4. Oil and ceramics industry

Condensed tannins are also commonly used in the oil and ceramic industries. In the bentonite oil-well muds in the United States, the main problem is the flow and suspension characteristics of bentonite. Tannins help to reduce the viscosity and increase the flow of bentonite (Hathway, 1962). Quebracho tannins are used widely to control the viscosity of the mud, and the annual consumption is around 30,000–40,000 tons for this purpose only (O'Flaherty et al., 1956). In the United States, it is accounted for about 40% of the total tannins consumption in 1950 (Anderson, 1955; Panshin et al., 1950).

Scientist reviewed the incorporation of condensed tannins by the ceramic industry. Quebracho tannins enable the use of higher solid mixer in the casting of clay slip by lowering the viscosity of the clay-water mixes. Condensed tannins save the plaster molds from deterioration by increasing the tensile strength of clay casts and eliminating the silica from the mixture, with consequent saving the deterioration of plaster molds. Quebracho tannins enhance the suspending power of the slip for the casting of bone in China (Hathway, 1962).

4.1.5. Anticorrosive chemical for metals

Tannins protect the iron materials from sulfate-reducing bacteria by exerting a bacteriostatic action (Farrer et al., 1953; Kusmierek and Chrzescijanska, 2015). Mangrove tannins are economically viable to protect the underground iron pipes and tubes (O'Flaherty et al., 1956; Shah et al., 2011). Condensed tannins have flavan-3-ol, which has oxygen atoms in its functional groups and aromatic rings, and aromatic ring can scavenge oxygen and inhibits corrosion (Gerengi and Sahin, 2012; Gerengi et al., 2012). The free electrons of oxygen get protonated in acidic media and the molecules of the protonated constituent are adsorbed on the metal surface because of electrostatic interaction and this inhibits the corrosion of metal (Singh et al., 2012, 2010). Tannate films of tannin extracts are formed on iron and steel surfaces to protect it from atmospheric corrosion (Byrne et al., 2019; Knowles and White, 1954). Similarly, for aluminum, a protective film is formed during the submersion of aluminum in tannin solutions and it reduces the active surface area, and inhibits oxygen reduction and metal dissolution. Thus, it can be used for the preservation of aluminum as well (Byrne et al., 2020; Nardeli et al., 2019; Stratta et al., 1956).

4.1.6. Preservation of wood

Condensed tannins can be used as wood preservative (Laks, 1987; Thevenon et al., 2010). Condensed tannins help to protect wood from fungal attack and increase the durability of wood (Thevenon et al., 2010; Tomak and Gonultas, 2018) as it works in the living plants. Scalbert et al. (1988) have mentioned that the phenolic compounds of tannins help to protect wood from rots of any kinds. Tannins along with hexamine evolves with wood (Kamoun et al., 2003; Pichelin et al., 2006), and maintains the mobility of boron with less leaching out to work as a fungicide (Pizzi and Baecker, 1996). Again, condensed tannins contain cathechol and epicathecin, which have ability to suppress the fungal activity (Hirasawa and Takada, 2004; Ichihara and Yamaji, 2009; Tascioglu et al., 2012, 2013; Tomova et al., 2005; Veluri et al., 2004; Yamamoto et al., 2000) and increase the durability of wood. Condensed tannins prevent wood from photodegradation by quenching $^1O_2$ and suppressing phenoxyl radicals (Chang and Chang, 2018).

4.1.7. Properties improvement of wood

Application of tannin-based formulation (tannin, hexamethylentetramine, sodium hydroxide, phosphoric acid and boric acid) in wood enhanced the bending, compression and hardness properties of scots pine and beech wood by around 20%. The tannin formulation makes a reticulation in the cells of wood, which helps to reinforce the mechanical properties of wood (Tondi et al., 2012). Besides, condensed tannins make a covalent bond with hemicellulose (Bariska and Pizzi, 1986) and proteins (Bariska and Pizzi, 1986; Capparucci et al., 2011), which strengthen or plasticize the cell walls and improve the strength properties of wood (Bariska and Pizzi, 1986). Yalcin and Ceylan (2017) concluded that tannins obtained from quebracho and mimosa impregnated into the wood with different varnish coating, which increased the protection of wood against different abiotic and biotic factors. Tannins also improve the dimensional stability of wood (Militz and Homan, 1994).

4.1.8. Improving the fire-resistance properties of wood

The tannin formulation (tannin, hexamethylentetramine, sodium hydroxide, phosphoric acid and boric acid) used to improve the wood properties also improves the fire-resistance properties of wood. The presence of phosphoric acid and boric acid in the formulation helps to improve the properties. The impregnation of tannin formulation reduced the ember time of scots beech wood by ten times (Tondi et al., 2012). Tannin as well as hexamine works as an anchor to develop a network with wood cell (Kamoun et al., 2003; Pichelin et al., 2006) and reduces the leaching out of the boron (Pizzi and Baecker, 1996). Therefore, tannin and boron work together to protect wood against fire.

4.1.9. Water and waste water treatment plant

Tannins have the potentiality to use as the water treatment chemicals (Ibrahim and Yaser, 2019; Meng et al., 2019; Ohara, 1994). Condensed tannins work as coagulant, which is used for treating wastewater. The condensed tannins extracted from *Picea abies* barks showed better coagulation efficiency compared to quebracho tannins (Bello et al., 2020). For better efficacy, the authors modified the both types of tannins following Mannich reaction with diethanolamine or ethanolamine and formaldehyde. The condensed tannins obtained from *Acacia mearnsii* also showed better efficiency for removal of anionic and cationic dyes from the wastewater (Grenda et al., 2020, 2018). Tannic acid is used in dye industry and water treatment process for purifying water (Ramakrishnan and Krishnan, 1994). Tannin-based commercial products are available in the market and are used to eradicate suspended colloidal matter like clay and organic matter. Chelating ability of tannin is important to remove the metallic ions, i.e., Cr, Ni, Zn or Cd from waste water (Hobbs, 2008).

A. mearnsii cryogel obtained from the extraction of *A. mearnsii* tannin with formaldehyde in alkaline medium is used as absorbent for heavy metal. Extraction of *A. mearnsii* tannin by epichlorohydrin in N, N-dimethylformamide medium, followed by grafting with diethylenetriamine and triethylamine yields as a cationic adsorbent. This cationic absorbent is also used for the removal of heavy metals from water (Combs, 2016). *A. mearnsii* cryogel is also applicable for the removal of dyes. It is noted that cationic dyes have higher adsorption efficiency than anionic dyes, like, tartrazine and alizarin violet. On the other hand, cationic adsorbent has a high efficacy for many anionic dyes, even for a cationic dye, such as, methylene blue (Combs, 2016). Anionic compounds, like, 2,4-D, MCPA, clofibric acid, acetylsalicylic acid, ketoprofen, diclofenac, naproxen are absorbed effectively whereas cationic products, such as, amoxicillin, atrazine and trimethoprim are adsorbed ineffectively (Combs, 2016). The use of condensed tannins (Wattle tannins) in the composite of cellulose microfibers can absorb methylene blue efficiently. The tannins provide binding site to absorb the methylene blue. Therefore, this can be used for sewage water treatment (Wang et al., 2019).

4.1.10. Packaging

Condensed tannin can also be used for the packaging materials. The use of 5 wt% quebracho tannins with cellulose nanofiber showed better tensile strength, thermal stability, ultraviolet (UV)-shielding ability and anti-oxidant biohybrid film. This film was used as the packaging material for food and other related materials (Li et al., 2019c). Phenolic units of tannin help to absorb UV (Li et al., 2019c), thus, the materials get protection against UV rays. Again, phenolic units suppress the hydroxyl radical formation by donating reducible hydrogen atoms (Andrade et al., 2005; Gulcin et al., 2010) and thus, tannin can work as anti-oxidant. On the other hand, the formation of good electrostatic attraction between cellulose and tannin enhances both thermal stability and tensile strength properties of tannin-cellulose biohybrid film (Li et al., 2019c).

4.1.11. Animal food

Condensed tannins help to utilize protein in the animal body by controlling the gastrointestinal parasites. Thus, condensed tannins are beneficial to animal health (Coop and Kyriazakis, 1999; Hoste et al., 2012; Juhnke et al., 2012; Lisonbee et al., 2009; Santos et al., 2020). Costes-Thire et al. (2019a, 2019b) found that the use of quebracho tannins extracted from quebracho tree (*Schinopsis lorentzii*) in the diet of sheep contributed the optimum utilization of protein by controlling *Haemonchus contortus* parasite. Dentinho et al. (2020) used condensed tannin of *Cistus ladanifer* in the soybean meal for the sheep and observed that the protein of soybean meal digested completely. The controlling of rumen protozoa was observed after incorporating tannins obtained from *Mimosa tenuiflora* in the diets of sheep by Lima et al. (2019). Additionally, quebracho tannins and chestnut tannins in the diets of cow were also used to increase the milk protein and decrease the nitrogen content in the urine (Aguerre et al., 2016, 2020).

4.1.12. 3D printing

In the recent days, condensed tannins are used in the 3D printing. Liao et al. (2020) observed that around 20% acetylated condensed tannin in poly lactic acid (PLA) and tannin filament composite provided good printing quality with better tensile property. For this case, the authors modified the mimosa tannins by using acetic anhydride in the presence of 1 wt% catalyst - pyridine.

4.2. Applications of hydrolyzable tannins

Hydrolyzable tannins are also used for various works. These tannins make complex interactions with protein. Thus, it has the ability to use for animal nutrition and industrial processing (Cadahia et al., 1996). This section discusses the applications of hydrolyzable tannins and these are summarized in Table 3.

Table 3
Sources and applications of hydrolyzable tannins studied by different researchers.

Types of application	Properties	Sources	References
Leather processing	Strong surface properties	Masuri berry	Guo et al. (2020)
Plastic resin and adhesives	Superior water resistance properties, exterior applications	Chestnut	Ghahri and Pizzi (2018); Vazquez et al. (2012); Vazquez et al. (2013); Spina et al. (2013)
Wood preservation	Fungal protective	Chestnut, tara	Tomak and Gonultas (2018)
Wine quality improvement	Improve wine flavor	Oak	Jordão et al. (2005); Puech et al. (1999); Viriot et al. (1993); Vivas and Glories (1996); Vivas et al. (1996)
Anti-corrosion agents for metals	–	Tara	Byrne et al. (2019)
Medication	Antimutagenic, anticancer, antioxidant, reduction of cholesterol	–	Ong et al. (1995); Smeriglio et al. (2017); Yugarani et al. (1993)

* (-) indicates that related information are not available in the respective literature.

4.2.1. Leather processing industry

For leather manufacturing process, the conversion of animal hide or skin into leather is considered as the main art of tanning in leather industries. To provide leather, tannin cross-links with the collagen chains located in the hide during tanning process. Hydrolyzable tannins obtained from plant extract are also widely used for tanning in leather industries (Ramakrishnan and Krishnan, 1994). Guo et al. (2020) found that the hydrolyzable tannins obtained from *Coriaria nepalensis* can make stable cross-linking with the collagen fibers of leather, which provides strong surface properties. The quality of the leather in terms of shrinkage, elongation at break, tear strength and tensile strength was comparable with the commercially available valonia tannin reagents.

4.2.2. Preparation of plastic resin and adhesives

Gallic acid used for manufacturing of plastic resins ((Ramakrishnan and Krishnan, 1994) and adhesives (Ramakrishnan and Krishnan, 1994; Vazquez et al., 2013) can be used to produce different types of composites. Ghahri and Pizzi (2018) studied the effectiveness of hydrolyzable tannin as adhesive for particleboard. The cross-linking of tannin by formaldehyde in the reaction of polycondensation can provide exterior category wood adhesive (Ghahri and Pizzi, 2018; Pizzi, 2009). Spina et al. (2013) concluded that hydrolyzable tannins can be used as adhesive for particleboard which can replace a significant portion of synthetic phenol from phenol-formaldehyde resin.

4.2.3. Preservation of wood

Hydrolyzable tannins can be used as wood preservative and thus, increase the durability of wood by protecting against fungal attack (Barry et al., 2001; Pizzi and Baecker, 1996; Tomak and Gonultas, 2018). Other researchers reported that tannin could protect wood against rots (Scalbert et al., 1998). These tannins with hexamine anchor in wood (Kamoun et al., 2003; Pichelin et al., 2006) and control the mobility of boron resulting lower leaching of it and act as fungicide (Pizzi and Baecker, 1996). Adiitionally, the gallic acid of hydrolyzable tannins reduces the fungal activity (Tascioglu et al., 2012, 2013) and increases the durability of wood.

4.2.4. Improvement of wine quality

Tannins play a great role on the quality of wine (Motta et al., 2020; Paissoni et al., 2020; Vignault et al., 2020). Hydrolyzable tannins contain polyphenols and antioxidant, which influence the wine quality (Motta et al., 2020). The tannin extracted from oak heartwood is commonly used to increase the flavor of wine in the wine industry. Besides, ellagitannins play a great role for controlling the color and flavor of wine during its aging (Puech et al., 1999). These tannins diffuse into the wine with the aging of wine in barrels (Jordão et al., 2005; Peng et al., 1991; Viriot et al., 1993; Vivas and Glories, 1996; Vivas et al., 1996) and help to increase the organoleptic quality of wine (Jordão et al., 2005). Ellagitannins also involve in the oxidation process of red and white wine (Moutounet et al., 1989) which absorb the dissolved oxygen quickly and facilitate the hydroperoxidation of the constituents (Vivas and Glories, 1996).

4.2.5. Anti-corrosion agents for metals

Tannins can be used as anticorrosion agent for mild steel and cast iron. The rusted steel is treated with mimosa tannins since 1976 (Hobbs, 2008). Sulfonated tannins are used to remove scale forming in the cooling water pipes and boilers. In the protective coating industry, tannins are used for protecting metal surfaces as a primer/undercoat/topcoat (Hobbs, 2008). Hydroxyl aromatic ring of hydrolyzable tannins scavenges oxygen and inhibits corrosion by blocking the metal surface through adsorption which enhances inhibition (Ostovari et al., 2009). Thus, the tannins can be used as anticorrosive to reduce or replace inorganic components, which are not environmentally friendly. *Caesalpinia spinosa* tannins were used for protecting metals from corrosion (Byrne et al., 2019).

4.2.6. Medication

Biological activities of hydrolyzable tannins confirm the beneficial effect of it on human health. It is used as antimutagenic, anticancer and antioxidant. Further, hydrolyzable tannins help to diminish serum cholesterol and triglycerides, and suppress lipogenesis by insulin (Ong et al., 1995; Smeriglio et al., 2017; Yugarani et al., 1993). Table 3

5. Potential uses of tannins

Properties of tannins have made them to consider for using in various purposes. It has the potential to use for various purposes such as, leather processing industry, wood industry, anti-corrosion of metal, water treatment plant, animal food, medical science and the production of advanced materials. Tannins are the major tanning material for converting animal hide/skin into leather. Actually, inorganic salts especially chrome salts are used to produce 70–85% leather. Replacing of toxic chrome salts with less toxic and environmentally friendly tanning materials is possible by polymerization of tannins with other synthetic materials (Hobbs, 2008).

Efficient extraction of tannins might also help to reduce the use of synthetic toxic materials. Most of the wood-based industries use adhesives and synthetic adhesives are hazardous to environment (Hobbs, 2008). There are several patents related to the tannins-based bioadhesive (Hobbs, 2008) which have confirmed the efficacy of condensed tannins as bioadhesives for composites industries (Kim and Kim, 2004; Pichelin et al., 2006). However, the main limitations of the adhesives are higher molecular weight, higher degree of polymerization, complex composition and slower rate of reaction (Liu et al., 2020). Thus, solving these issues by nucleophilic reagent acidolysis (Li et al., 2019b; Mouls and Fulcrand, 2015), sulfite treatment (Xiang-ming et al., 2007), mercaptoethanol treatment under acidic condition (Li et al., 2019a) and NaOH/urea treatment (Liu et al., 2020) can help to use tannins as adhesives by the wood-based industries. The tannin-modified phenolic resin or tannin alone can provide better strength properties with lower or zero formaldehyde emission (Li et al., 2019b, 2004; Liu et al., 2020; Osman, 2012). Therefore, tannins can be used as alternative source of adhesive in wood composite industry (Hobbs, 2008). Additionally, the improvement of wood properties like strength, fire resistance and durability of wood using condensed tannins (Laks et al., 1988; Thevenon et al., 2010; Tondi et al., 2012) and hydrolyzable tannins (Ramakrishnan and Krishnan, 1994; Tascioglu et al., 2012, 2013) was confirmed by previous investigations. Although, pH of tannic acid with higher temperature corrodes knives in the wood industry (Winkelmann et al., 2009; Zelinka and Stone, 2011), it might be possible to get the aforementioned benefits to use tannins as important materials in wood-based industries.

The color of 3D printed objects using tannin as binding agent is brown having the printing temperature is 220 °C for avoiding thermal degradation (Liao et al., 2020). Thus, further research is needed to overcome the problem of color and printing temperature issues for obtaining better quality 3D printed objects incorporation with tannins. Zhang et al. (2019) developed promising low cost tannin/graphene oxide composite material to recover germanium. Tannins can be used for value-added biomass conversion, i.e., fatty acids to fatty alcohols (Gou et al., 2020). Condensed tannins negatively affect the bioethanol production by inhibiting the fermentation process resulting in lower amount of ethanol production from rice straw (Shi et al., 2020; Wang et al., 2017). Thus, the extraction of condensed tannins from the straw prior to bioethanol production can provide the optimum bioethanol production. Bio-based foams, glucose-based non-isocyanate polyurethane foams, were produced using mimosa tannin, pine tannin and Norway spruce bark tannin (Chen et al., 2020a, 2020b; Lacoste et al., 2013, 2015; Zhou et al., 2019). In another study, condensed tannins obtained from the barks of radiata pine were used to produce polyurethane foams. All these bio-based foams showed better strength and higher thermal stability, which showed their potentiality for building construction (Hussain et al., 2020). Besides, tannins can also be used as a viscosity modifier of mud for the production of residential and architectural bricks, which enhance the production and quality of bricks (Hobbs, 2008). Further steps are needed to use these potentialities of tannins efficiently.

Tannins have the potentiality for dye decolorization in the Fenton and photo-biocatalytic technique by modifying $NiFe_2O_4$ nanoparticles with tannins (Atacan et al., 2019; Romero et al., 2020). Condensed and hydrolyzable tannins can be used for removing fungal film from bioreactors (Spennati et al., 2019). Mimosa tannins can be used for the production of micro-mesoporous carbons to adsorb CO_2, organic volatile compounds and dye molecules (Phuriragpitikhon et al., 2020). A study has been conducted to build an ionic channel by forming bilayer lipid membranes in native cells of algae using hydrolyzable tannins obtained from smooth Staghorn sumac leaves. The use of hydrolyzable tannins can block Ca^{2+} dependent chloride. Therefore, the tannin can help to make biomembranes (Borisova et al., 2019) as well as to produce energy storage devices (Hu et al., 2020).

The benefits of tannins for animal nutrition have been discussed in the previous sections. However, the higher dosage of tannin in the diets of cow can reduce the feeding efficiency, production and digestibility (Aguerre et al., 2016, 2020). Again, condensed tannins are used to preserve lignocellulosic materials naturally for controlling the insects, pest, and fungus. Thus, condensed tannins have the potentiality to use as environmentally friendly biocides (Laks, 1987).

The effects of tannins on the human health is still contradictory (Puech et al., 1999), however, it is quite natural that higher dosage of tannins is health hazardous (Cao et al., 2020). Several studies showed that tannins have anti-carcinogenic (Puech et al., 1999), antiviral, anticancer, antibacterial, antiflammatory and anti-oxidant properties which might be the driving force to use as medicinal products (Hobbs, 2008; Ogawa and Yazaki, 2018). Thus, researchers are working for developing medicines from tannins (Hobbs, 2008; Ogawa and Yazaki, 2018). Proanthocyanidins (flavonoids) extracted from black wattle can be used as supplement of health food to control the blood glucose (Ogawa and Yazaki, 2018). Condensed tannins obtained from the barks of wampee tree have novel α-glucosidase and tyrosinase inhibitor, which can be used for skin disease and anti-diabetic agents (Chai et al., 2019). The aggregation of α-synuclein protein, a small neuronal protein, is the main causative component for Parkinson disease, can be inhibited by using tannins 1,3,6-tri-O-galloyl-β-D-glucose and 1-O-galloyl-2,3-hexahydroxydiphenoyl-4,6-valoneoyl-β-D-glucose which can be obtained from spurge and caper spurge, respectively (Sekowski et al., 2020). The banana condensed tannins obtained from green-mature banana can be used to reduce the toxicity of glyphosate (Zeng et al., 2020a) and interaction with biologically important metal ions (Zeng et al., 2019). The condensed tannins obtained from green-mature apple can be used to control the cholesterol (Zeng et al., 2020b). Thus, all these potentialities of tannins in medical science need further study. Several studies have done to make chemical marker by gallic acid extracted from oak dust to identify the exposure to oak wood dust (Carrieri et al., 2016). The condensed tannins obtained from black wattle have been used to develop hemocompatible surface for biomedical device. The presence of similar mussel adhesive protein, catechol groups, in condensed tannins helps to work as platelet repellant (da Camara et al., 2020). Thus, there is a possibility to use tannin in the production of biomedical devices. All the research activities indicate that the uses of tannins are getting popularity. There are many uses of tannins for the welfare of human being, and continuous research is being carried out for increasing the diversity of utilization of tannins.

Conclusion

Tannins are an important natural chemical found in different forms especially in the plants. Condensed and hydrolyzable tannins are the two main types of tannins found mainly in the barks, leaves, fruits, shell of fruits, seeds, shoots and stems. Tannins from those sources can be extracted with water alone or water with other solvents, i.e., methanol, ethanol, acetone, sodium hydroxide and ionic liquids. Several advanced technologies, i.e., microwave, utrasonication have shown potentiality to extract tannins efficiently. The purity of tannins is very important for the applications, which depend on the solvents and technology. Besides, the control of temperature, solid to solvent ratio, size of the particle, sources and extraction time help to get better quality of tannins. Commonly, carbohydrate contaminates tannins during the extraction process, which restricts its applications. Depending on the types of tannins, applications vary, i.e., wood adhesive, wood properties improvement, water treatment, anticorrosion of metals, animal food etc. Antimicrobial activity of tannins results in using for packaging materials. Alongside, tannins have some other advanced applications such as supplement foods, medicines, bio-based foams, 3D printing, and development of biomedical devices. However, all the applications need further studies, which might open new dimensions for the applications of tannins. This work will help to overcome/at least set up guidelines for a research to overcome the hurdle in the advanced applications and consider the extraction of hardwood tannins broadly.

Declaration of Competing Interest

None

Acknowledgement

None

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