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REVIEW ARTICLE

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Possibilities and challenges for harnessing tree bark extracts for wood adhesives and green chemicals and its prospects in Nepal

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ABSTRACT
Tree bark contains anti-microbial, antioxidant, and anticancer compounds and are therefore widely used by pharmaceutical, cosmetics, and food industries as raw materials. Bark provides raw materials for adhesives, insulating materials, and even water purification. The article reviews the utilization of tree bark as a source of green chemicals and adhesives and the possibilities of their application in Nepal. The study also shows the direct utilization of bark as an insulating material and the extraction of chemicals as therapeutic. The extraction of chemicals from bark differs from species to species due to variations in chemical compositions. The study shows that despite the versatility of tree bark, Nepal hasn't been using its benefits and utilized it just as waste. Finally, this paper discusses the perspective and challenges in the production of chemicals and materials from the bark.

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Adhesive; green chemicals; Nepal; tannin; tree bark

1. Introduction

Tree bark is an underutilized forest residue that consists of cellulose, hemicellulose, lignin, and a variety of extractives, such as tannin, suberin, terpenoids, starch, and sugars (Pásztory et al. 2016; Chen et al. 2020; Giannotas et al. 2021). This underused renewable resource involves 9–15% of a typical wood log by volume and it even causes disposal problems (Harkin and Rowe 1971; Pásztory et al. 2016). Therefore, many types of research were carried out to explore the potentialities of tree bark utilization in the design of novel products. Also, bark utilization provides environmental, technical, social, and economic benefits as well (Kuo et al. 2019).

Tree bark has been utilized since ancient times for different reasons. For example, Himalayan Birch (*Betula utilis* D. Don) bark was used centuries ago as paper for writing scriptures and texts in Sanskrit (Singh et al. 2012). Egyptians applied bark-derived resins on coffins for mummies (Austin 1994), and Asians Red Sanders (*Pterocarpus santalinus* L.) bark extract was utilized for treatments of tumors and urethral discharges (Keshavamurthy et al. 2018). The comprehensive research on bark was started around 1930 for systematic utilization for industries (Austin 1994). In 1982, spruce bark was used as a constituent of plywood adhesives (Liiri et al. 1982), and afterward a considerable number of bark extraction technologies and bark-based products were patented (Chemat et al. 2012; Zhang et al. 2018). The bark of several tree species has been extensively utilized in current technologies or in conjunction with them. Tree bark extract has been utilized in the green synthesis of gold nanoparticles (Bahram and Mohammadzadeh 2014; Keshavamurthy et al. 2018; Burlacu et al. 2019), insulation (Parvin et al. 2019; Busquets-Ferrer et al. 2021; Giannotas et al. 2021), wastewater treatment (Parvin et al. 2019), bioindicators of pollutions (Santamaría and Martín 1997; Birke et al. 2018; Patel et al. 2020), adhesives (Ndiwe et al. 2019; Tahir et al. 2019), medicinal compounds (Šiman et al. 2016; Srivastava et al. 2016; Elansary et al. 2019), and food industry (Mármol et al. 2019). The use of bark-derived chemical compounds could help to solve environmental and economic problems at the same time (Diouf et al. 2009). The above-mentioned shows that the utilization of bark has been practiced Mohammadzadeh for centuries in different forms due to its special chemical components and unusual structure. The two biggest potential applications of bark constituents are green chemical synthesis and in adhesive systems and foams.

VTT Technical Research Center of Finland has undertaken a research program on the chemical utilization of willow bark in biodegradability, UV-shielding, and antioxidant properties for medical, pharmaceutical, and food applications (Lohtander et al. 2021). Likewise, the Forest Product Laboratory of the United State has conducted research since 1971 to date on efficient bark utilization by new industries to boost the economy by making a valuable asset out of costly waste (Harkin and Rowe 1971; Eberhardt et al. 2016). Chemical and structural characterization showed *Albizia niopoides* (Spruce ex Benth.) Burkart tree bark

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from Amazon rich in phenol, namely flavonoids and tannins with antioxidant activity (Carmo et al. 2016). Navid et al. (2014) examined the bark of *Betula pendula* as antiviral characteristics for certain herpes viruses, and Comandini et al. (2014) isolated seven compounds (vescalin, castalin, gallic acid, vescalagin, 1-O-galloyl, castalagin, and ellagic acid) from the bark of *Castanea sativa* Mill. which are traded as dietary supplements. Pyrolysis of Durian bark produced acetic acid, wood spirit (alcohol methylicus), 2-propanon, and phenol as a green chemical for industries (Oramahi and Diba 2013). Venter et al. (2012) found *Acacia mearnsii* De Wild bark as a good source of natural polymers which can be used as tanning agents and adhesives. Bark compounds have a higher number of aromatic groups and a lower average molecular weight than wood compounds, which makes them suitable for use in adhesives and foams (Kuo et al. 2019). In addition, growing environmental awareness and strong regulation of formaldehyde [carcinogenic, recognized by the World Health Organization (WHO)] urges the industry to develop environmentally friendly adhesives (Liteplo et al. 2002; Todorovic et al. 2021). Antonio Pizzi is the biggest contributor to the development of several types of tannin adhesive for plywood, particleboard, and laminated products (Pizzi 2008; Brosse and Pizzi 2017; Tahir et al. 2019). Many studies showed tree bark as a good bio-based polymer for wood adhesives (Chen and Yan 2018; Réh et al. 2019; Tudor et al. 2020), however, it has proven challenging to replace synthetic adhesives since bio-based polymers often have poor bonding performance, particularly in terms of water resistance, and/or are not cost-competitive. Another issue in substituting synthetic polymers is the wide range of properties of bio-based polymers, which are influenced by locus, type of source, growing season, growth circumstances, and extraction technique (Ek et al. 2009; Cywar et al. 2021). Bio-based polymers are materials which are produced from renewable resources. In addition, they often need to include synthetic components, such as isocyanates or epoxides, which cannot be considered "green" (Heinrich 2019). Polysaccharides, the major chemical composition in bark has poor water resistance, therefore commercialization of starch-based wood adhesive is challenging (Patel et al. 2013).

There is substantial research carried out on the chemical extraction and the application of tree bark. However, there is no extensive review, particularly focusing on possibilities and associated challenges in the extraction of green chemicals with their applications. Thus, this review paper provides a broad overview of the topics, covering extraction techniques and associated challenges, existing use, and future applications of tree bark in other applications.

The studies for this review were chosen from Springer, Google Scholar, and Science Direct as they cover a wide range of articles on the topic. The search descriptors used were tree bark extract, potentials of tree bark extract, challenges in tree bark utilization, adhesive from tree bark, and tree bark utilization in Nepal. The articles published between 2015 to 2021 were collected to understand the recent trends and relevance of research on the topics. Only articles published in English that were registered on the journal website were included in the study.

The abstract of each article was reviewed individually based on title and abstract content. In case of conflict, an independent review was made and decisions were made based on inclusion and exclusion criteria. To eliminate subjectivity in the data gathering and selection procedure, both reviewers (SP and PP) independently extracted and assessed the data. Separate tabulations were made for possibilities and challenges with standardized information, such as features of publication (author, country, and year), tree species, extraction methods, and type of extract used. Contact with the authors was done when we faced difficulties in extracting data. Following that, the data were compared, and any discrepancies were detected and addressed through discussion to obtain a consensus among the reviewers. All the searched articles in different search portals were imported and managed using Mendeley reference management software (Mendeley Desktop version 1.19.4).

2. Results

The initial search generated 737 studies from different databases [(Google scholar ($n = 37$), Springer ($n = 286$), ScienceDirect ($n = 345$), and CORE ($n = 69$)] using the different descriptors on the topics. Studies that did not meet the pre-determined criteria were ignored. Three hundred and twenty-seven papers did not report the utilization of tree bark as a green chemical or adhesive and some had little significance in literature reviews. Finally, a total of 34 articles were used for end analysis out of which 28 were related to green chemicals and six related to wood adhesives. The articles cover 17 countries studying the utilization of tree bark as a green chemical and adhesive (Table 1). Out of 34 articles, four publishes in 2015, four in 2016, three in 2017, five in 2018, six in 2019, 3 in 2020, and nine in 2021.

Hot water extraction (uses distilled or deionized water), aqueous extraction (distilled water or organic solvent) and hydrodistillation (uses water, steam, or a combination of water and steam) were the most common extraction methods for substances profiling from the bark. In the study both *in vitro* and *in vivo* methods were utilized to understand the prospects of bark extracts as therapeutics. A review of articles showed tree bark was extensively used as medicine, wood adhesive, bio-insulation, and natural dye. The authors of the selected articles were experts in the field and highlighted the use of bark as an environmentally sustainable natural product. Most of the researchers raised concerns about the cost of processing tree bark and providing a cost-effective method of making tree bark extract an attractive and potential raw material. This called for more research and in-depth knowledge on

Table 1. Articles included in the study.

Tree species	Geographical distribution	Application	Type of wood	Active constituents	References
Abies alba Mill., *Larix decidua* Mill., *Picea abies* (L.) H. Karst., *Pseudotsuga menziesii* (Mirb.) Franco and *Pinus sylvestris* L.	Europe	Adhesive	Softwood	Phenolic monomers, condensed tannins	Bianchi et al. 2015
Acacia catechu (L.f.) Willd	India	Industrial application	Hardwood	Total phenol	Kumar et al. 2019
*Acanthopanax sessiliflor*u	Korea	Effective for the treatment of human breast cancer	Hardwood	*n*-Hexane, butanol	Thamizhiniyan et al. 2015
Alnus glutinosa Medik.	France	Antimicrobial activity	Hardwood	Methanol	Abedini et al. 2016
Caesalpinia sappan L.	India	Dye toxicity in rats	Hardwood	Aqueous extract	Athinarayanana et al. 2017
Ceriops Decandra (Griff.) Ding Hou.	Bangladesh	Particleboard production	Hardwood	Phenols	Nath et al. 2018
Cinnamomum loureirii	China	Antioxidant potential varied with age	Hardwood	Total phenol and flavonoid	Li et al. 2021
Cinnamomum zeylanicum (Breyne)	Korea	Biofilms production	Hardwood	Cinnamaldehyde	Kim et al. 2015
Cinnamomum zeylanicum (Breyne)	India	Cytotoxic effect	Hardwood	Cinnamaldehyde	Husain et al. 2018
Copaifera langsdorffii Desf.	Brazil	Natural dye	Hardwood	Tannins	Carmo et al. 2016
Croton lechleri Mull. Arg.	Brazil	Antioxidant activity	Hardwood	Gallic acid	Diedrich et al. 2021
Croton urucurana Baill.	Brazil	Natural dye	Hardwood	Tannins, lignin	Silva et al. 2020
Endopleura uchi (Huber) Cuatrec	Brazil	Lifespan of Nematode	Hardwood	Polyphenol	Peixoto et al. 2019
Eucalyptus urophylla S.T. Blake.	Brazil	Biorefinery raw material	Hardwood	Total phenol	Sartori et al. 2021
Ficus religiosa L.	India	Antiviral activity	Hardwood	Flavonoids, tannins	Cagno et al. 2015
Juglans regia L.	India	Natural dye	Hardwood	Potassium aluminum sulfate	Ali Khan et al. 2016
Mimosa tenuiflora (Willd.) Poir.	Brazil	Wood adhesives	Hardwood	Tannins	Lopes et al. 2021
Myrcia eximia DC	Brazil	Wood adhesives	Hardwood	Tannins	da Silva Araujo et al. 2021
Phellodendron amurense f. mole (Nakai) W. Lee., *Humulus japonicus* Siebold & Zucc.	Korea	Improving the quality of blastocysts of Bovine	Hardwood	Melatonin	Do et al. 2017
Picea abies (L.) H. Karst.	Finland	Antimicrobial and antioxidant potential varied with UV-irradiation	Softwood	Stilbene composition	Välimaa et al. 2020
Picea abies (L.) H. Karst.	Switzerland	Influence of bark aging	Softwood	Oligosaccharides, Phenolic monomers	Bianchi et al. 2016
Pinus brutia Ten	Turkey	Preservation of sperm quality of Bulls	Softwood	Phenolic compounds	Taşdemir et al. 2020
Pinus sylvestris L., *Picea abies* (L.) H. Karst., *Betula pubescens* (Ehrh.) Spach	Norway	Anthelmintic drugs	Softwood and hardwood	Tannins	Athanasiadou et al. 2021
Platanus acerifolia (Aiton) Willd.	Hungary	Medicinal purposes	Hardwood	Triterpenoid	Plánder et al. 2019
Populus nigra L., *Populus alba* L	Austria	Thermal insulation	Hardwood	Alkaline extraction	Busquets-Ferrer et al. 2021
Quercus rubra, Prunus serotina Ehrh., *Quercus robur* Pall, *Betula pendula* Roth., *Fraxinus excelsior* Boiss, *Robinia pseudoacacia* L., *Carpinus betulus* L., *Picea abies* (L.) H. Karst., *Alnus glutinosa* Medik., *Pinus sylvestris* L	Hungary	Antioxidant capacities for the food industry	Hardwood and softwood	Polyphenol	Agarwal et al. 2021

(*continued*)

Table 1. Continued.

Tree species	Geographical distribution	Application	Type of wood	Active constituents	References
Stryphnodendron pulcherrimum (Willd.) Hochr.	Brazil	Antibacterial activity	Hardwood	Gallic acid, gentisic acid, benzoic acid	Gomes et al. 2021
Terminalia brownii Fresen., *Terminalia laxiflora* Engl., *Anogeissus leiocarpus*	Sudan	Antibacterial potential	Hardwood	Gallic acid, gallotannin, ellagitannin, ellagic acid	Salih et al. 2017
Terminalia			*arjuna* (Roxb.) Wight & Arn.	India	Antimicrobial and antioxidant potential
Hardwood	Phenols, flavonoids, tannins	Kumar et al. 2018			
Tetrapleura tetrapteura Taub.	Cameroon	Toxicity effects on mice	Hardwood	Aqueous extracts	Dongmo et al. 2019
Thuja plicata Lamb.	Canada	Wood adhesives	Softwood	Polymeric diphenylmethane diisocynate (B-pMDI)	Chen and Yan 2018
Virola elongata (Benth.) Warb.	Brazil	Gastroprotective and antiulcer activity	Hardwood	Total phenols, total flavonoids and alkaloids	Almeida et al. 2019
Vitex doniana Sweet	Nigeria	Medicated soap	Hardwood	Saponins, phenols	Shuaibu et al. 2018
Warburgia salutaris (G. Bertol.) Chiov.	South Africa	Treatment of Skin and respiratory pathogens	Hardwood	Drimenol and E-nerolidol	Khumalo et al. 2019

bark utilization economically, socially, and environmentally.

3. Discussion

Tree bark possesses a complex chemical composition, therefore, covers a wide range of interests from anatomy, physiology, chemistry, physical and mechanical properties, utilization, and debarking. There is considerable literature on the utilization of tree bark but only relatively little economic uses due to complexity and large variation between barks of different species. Many industrial products have been produced using green chemistry for and from wood, such as biosourced, greenwood adhesive and preservative, composite matrices, and hard and flexible plastics, and their number is still increasing (Pásztory et al. 2016; Pizzi 2016). Broadly, this utilization is categorized into two major headings, i.e. bark utilization as green chemical and adhesives.

3.1. Tree bark utilization as green chemicals

Tree bark has a variety of high-value chemicals, therefore, is considered a potential resource for biorefineries and pharmaceuticals (Harkin and Rowe 1971; Hamad et al. 2019). The knowledge of these chemical constituents would be of great help for the development of different green products with efficient conversion technologies.

The bark of Plane Tree [*Platanus acerifolia* (Aiton) Willd.] is rich in Triterpenes (Betulin, betulinic aldehyde, and β-sitosterol) is used as an inhibitor for the replication of cancer cells. The Betulin can be easily converted to betulinic acid (Jung and Duclos 2006) which inhibits the Human Immuno Deficiency Virus (Plánder et al. 2019). The bark of the Nordic tree (Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* L. H. Karst.). and Downey birch (*Betula pubescens* Ehrh. Spach) extract showed anthelmintic efficacy against the ovine infectious nematode (*Teladorsagia circumcincta*). The extract with low condensed tannins showed low activity of nematode indicating commercially used tree bark as a potential alternative to anthelmintic (Athanasiadou et al. 2021). Likewise, Brazilian tree bark (*Endopleura uchi* Huber) Cuatrec which contains polyphenol bergenin and increases the lifespan of the nematode (*Caenorhabditis elegans*) independent from caloric restriction supporting bark extract having anti-aging and anti-oxidant properties (Peixoto et al. 2019). In Nigeria, Black Plum bark (*Vitex doniana* Sweet) extract has antibacterial and antifungal activities and is used to prepare medicated soap toward a skin infectious bacteria *Staphylococcus aureus* (Shuaibu et al. 2018).

The Red pine bark (*Pinus brutia* Ten) extract prevents chromatin damage and sperm quality of bulls by reducing oxidative stress (Taşdemir et al. 2020). Native plants from Korea, i.e. *Phellodendron amurense* f. mole (Nakai) W. Lee and *Humulus japonicus* Siebold & Zucc have oxidative and antioxidant enzymes that help to improve the quality of blastocysts of Bovine by reduction of reactive oxygen species and apoptosis (Do et al. 2017). In tropical southeast Africa, the bark of *Warburgia salutaris* (G. Bertol.) Chiov. is used to treat a wide variety of illnesses caused by fungi, bacteria, viruses, and insects (Khumalo et al. 2019). Also, Drimenol and E-nerolidol, two main constituents of *W. salutaris* bark are used in treating skin and respiratory ailments. Abedini et al. (2016) studied the extract from the bark of *Alnus glutinosa* Medik. and found that they have high-level antimicrobial activity against certain viruses. Aqueous bark extracts from ten common wood species from Hungary (*Quercus rubra*, *Prunus serotina* Ehrh., *Quercus robur* Pall, *Betula pendula* Roth., *Fraxinus excelsior* Boiss., *Robinia pseudoacacia* L., *Carpinus betulus* L., *Picea abies* L. H. Karst., *Alnus glutinosa* Medik, *Pinus sylvestris* L.) have antioxidant properties with possible utilization in the food industry (Agarwal et al. 2021). *Terminalia arjuna* (Roxb.) Wight & Arn bark is rich in phenolic and flavonoid content making it antioxidant and antimicrobial therapeutics (Kumar et al. 2018). *Tetrapleura tetrapteura* Taub. is widely used to treat many diseases, such as gastric ulcers, malaria, and rheumatism in tropical Africa. Therefore, Dongmo et al. (2019) studied the acute toxicity dose of *Tetrapleura tetrapteura* Taub. stem barks on rats and mice and found acute administration (200 mg/kg) is safe and a higher dose (400 mg/kg) for a longer period induces harmful effects on the hematopoietic and hepatic systems.

The bark of *Virola elongata* (Benth.) Warb is traditionally used for the treatment of stomach pain, indigestions, and gastric ulcers in the North and Midwestern regions of Brazil. Almeida et al. (2019) demonstrated the effectiveness of this bark extract in the treatment and prevention of gastric and peptic ulcers with antioxidant activity. *Acanthopanax sessilifloru* stem bark contains methanolic compounds that induce human breast cancer cell death-like necrosis (Thamizhiniyan et al. 2015). Kim et al. (2015) examined the effects of essential oils of cinnamon bark, finding that some components effectively hinder the formation of microorganisms. A study in Brazilian tree bark (*Stryphnodendron pulcherrimum* Willd. Hochr.) prove to have excellent antibacterial action. The ointment-based extract from the species had good absorption and did not irritate the skin in mice suggesting a wide safety margin at therapeutic doses (Gomes et al. 2021). The ethanolic bark extract of *Cinnamomum zeylanicum* Breyne was demonstrated to possess anticancer activities and is beneficial in integrative cancer therapy against proliferation, metastasis, and migration of breast cancer cells (Husain et al. 2018). *Terminalia brownii* Fresen, *Terminalia laxiflora* Engl., and *Anogeissus leiocarpus* bark are rich in ellagitannins, ellagic acid derivatives, flavonoids, and stilbenes and are used for the treatment of infectious diseases and their symptoms in Sudan (Salih et al. 2017). Diedrich et al. (2021) studied the *Croton lechleri* Mull. Arg. barks and isolated phenolic compounds that have an antioxidant activity that can be utilized as a natural additive in food technology, pharmaceutical, and chemical industries. In China, *Cinnamomum loureirii* bark extract which is rich in essential oil, phenolic acid and flavonoids is utilized by the food, perfumery, cosmetic and pharmaceutical industries. Studies showed medicinal compounds present in the tree bark varied depending on the age of the tree with the highest content from 12 to 15 years (Li et al. 2021). Likewise, Norway spruce (*Picea abies* [L.] Karst.) inner bark rich in stilbene increased the radical scavenging activity by inducing UVA-irradiation (Välimaa et al. 2020). This showed the influence of external factors on the quality and quantity of antioxidants and antibacterial compounds. The *Ficus religiosa* L., a sacred plant bark, showed antiviral activity against two respiratory viruses that are associated with wheezing illness and asthma exacerbation (Cagno et al. 2015). Further research on bark extract could be done to identify other potential therapeutic properties.

3.2. Tree bark utilization as a natural dye

Tree bark extracts are utilized as natural dyes as they are biodegradable with low toxicity and generate low levels of allergic reaction. The *Croton urucurana* Baill., native to Brazil, contains tannin which is found to be a potential natural dye with color-fastness properties for textile dyeing (Silva et al. 2020). In another study, *Copaifera langsdorffii* Desf. bark extract is rich in phenolic compounds that are potential natural dye sources for wool fabric (Carmo et al. 2016). Walnut (*Juglans regia* L.) bark exhibits good staining quality on woolen yarn giving a variety of light and bright grayish to yellowish-brown shades of varying depth (Ali Khan et al. 2016). *Caesalpinia sappan* L. bark is used as a natural dye in many consumer products; Athinarayanana et al. (2017) studied the toxicity of the bark extract in albino rats and found no clinical signs of toxicity and mortality even at a dose level of 100–2000 mg/kg for 14 days indicating it as a safe red dye that can be utilized as a food colorant and good for human health. This showed that tree bark extracts are natural dyes that are cheap, nontoxic, and sustainable resources with minimal environmental impact.

3.3. Bark-based adhesives for plywood

Bark constitutes a valuable component known as tannins which could be used as eco-friendly wood adhesives. Tannin-based adhesives have been studied since the 1950s. For forty years, a wattle bark tannin-based glue has been used commercially in the Southern Hemisphere and in Europe for exterior-grade particleboard (Pizzi and Merlin 1981).

Tannin extracts from European softwood species (Norway spruce (*Picea abies* [Karst.]), Douglas fir (*Pseudotsuga menziesii* [Mirb.]), and Scots pine (*Pinus sylvestris* [L.]) bark show an impressive level of purity that can be applied as an adhesive for fiberboard and particleboard (Bianchi et al. 2015, 2016). This might replace the utilization of formaldehyde with bio-based adhesive for use in the wood-based panel manufacturing industry. The temperature at which bark tannin is extracted affects its reactivity, with the degree of this impact varies depending on the type of bark and the extraction solvents. The bark of a common mangrove species [*Ceriops Decandra* (Griff.) Ding Hou.] showed the highest viscosity (512 cP), modulus of elasticity (948 MPa) with reduced moisture content, water absorption, and thickness swelling of the particleboards (Nath et al. 2018). The bark of *Myrcia eximia* DC. was studied by da Silva Araujo et al. (2021), with high levels of condensed tannins for application in a natural adhesive. Moreover, they found extraction in sodium sulfite solution promoted the highest yields of tannins compared to extraction performed only in water.

Chen and Yan (2018) used the bark of the Western red cedar (*Thuja plicata* Lamb.) tree as a reactive function filler in polymeric diphenylmethane diisocynate (pMDI) wood adhesive to improve the bondline formation at the adhesive-substrate interface and found lower activation energy and a higher reaction rate for pMDI curing with moist bark than with oven-dry bark. Also, FTIR characterization of the bark suggests the existence of urethane and urea linkages in the cured adhesive. Three types of tannins were extracted from *Mimosa tenuiflora* (Willd.) Poir. bark using different aqueous solutions (a pure aqueous solution, a 5% sodium hydroxide (NaOH) aqueous solution, and a 5% sodium bisulfite ($NaHSO_3$) aqueous solution) and applied for bonding pine wood joints (Lopes et al. 2021). The tannins-based adhesives showed high viscosities and yielded bond lines with similar shear strengths if compared to each other. *Eucalyptus urophylla* S.T. Blake tree bark has a high content of phenol, flavonoids, and tannins but with weak antioxidant properties making it a good source of triterpenic acids (ursolic and betulinic acids) that can be utilized as a feedstock for biorefineries (Sartori et al. 2021). The study showed mixing aqueous tannin with hardeners, such as paraformaldehyde, hexamethylenetetramine, tris(hydroxylmethyl) nitromethane, and glyoxal or polymeric 4,4′ diphenylmethane diisocyanate (pMDI) is the most popular method for tannin-based resin synthesis. Though the uses of tannin are useful its application is limited due to its low solubility, high viscosity, and too high or low reactivity which needs to be adjusted. Alkaline extract from poplar bark (*Populus nigra* L. and *Populus alba* L.) reduced the mass of specimens and increased volume than untreated bark thereby suggesting a viable bio-based alternative to fossil-based thermal insulation materials (Busquets-Ferrer et al. 2021). This suggests that bark is a potential bio-based insulation material that is available in higher quantities, but further research is needed on the up-scaling of the product.

3.4. Tree bark for harnessing green chemicals and adhesives in Nepal

Forest resources are significant for the ecosystem balance and people’s livelihood in Nepal. There are 35 major forest types and 118 ecosystems found in Nepal making the country reach in natural resources (DFRS 2015). Nepalese utilize different tree barks for medicinal purposes; however, their commercial utilization is still lacking due to poor research and development (Table 2). The bark of Timur (*Zanthoxylum armatum* DC. syn *Z. alatum* Roxb.) contains alkaloids, flavonoids, terpenoids, phenols, etc., and is extensively used in indigenous medicine (ache, fever, toothache, tonsillitis, diarrhea, dysentery, altitude sickness) (Hertog and Wiersum 2000; Phuyal et al. 2019). More studies on the plant are needed to establish a strong linkage between indigenous medicines and modern scientific research that opens the underlying capabilities of the plant and its relevant therapeutic activities. Neem (*Azadirachta indica* A. Juss.), rich in antioxidants, is used for the treatment and prevention of various diseases and is widely found in Nepal (Karki and Karki 1993). A recent study by a group of scientists from the University of Colorado School of Medicine showed *Azadirachta indica* bark extract contains triterpenoids allowing it to competitively target a panoply of viral proteins inhibiting mouse and human coronavirus infections (Sarkar et al. 2022).

The stem bark of *Cinnamomum zeylanicum* Breyne extract contains lactose and stearic acid and is effective for the treatment of type-2 diabetes mellitus (Ranasinghe et al. 2017). The study showed an extract from *Cinnamomum zeylanicum* is a mediator for the green synthesis of bioresources and biomaterials with antimicrobial activity (Sathishkumar et al. 2009). Also, the *Cinnamomum zeylanicum* bark contains cinnamaldehyde and eugenol with considerable antioxidant, antimicrobials, and moderate cytotoxic activities (Sharma et al. 2016) providing new insight to research for utilization of these compounds for food and medicinal applications.

Pterocarpus marsupium Roxb, an endangered medicinal plant bark contains important phytochemical constituents that have antioxidant, antibacterial, antidiabetic, and anti-inflammatory activities and varied between trees and sites (Pant et al. 2017). An evergreen broad-leaved tree, Kaulo [*Persea odoratissima* (Nees) Kosterm.] found in mid and far western Nepal is traditionally used for snake bites, burn wounds, and antiseptic and anti-inflammatory remedies. *Persea odoratissima* bark is traded in huge quantities to India and China in raw form at a low price, therefore research on its bark extracts would help in the development of new products (Pyakurel et al. 2018). *Pinus roxburghii* Sarg. tree bark contains 38 different chemical constituents of anti-microbial and cytotoxic activity due to the high concentration of terpinene-4-ol, (E)-caryophyllene, and α-humulene (Satyal et al. 2013). Chaphalkar et al. (2017) found Amala (*Phyllanthus emblica* L.) bark is rich in total phenols, total flavonoids, and total tannins with hepatoprotection and antioxidant activity. However, further studies are needed to identify and isolate the polyphenolic compounds, which then could be used for patients with alcoholic liver disease. *Myrica esculenta* Buch.-Ham. ex D. Don has been shown to have a variety of pharmacological effects in the treatment of diseases, such as asthma, diabetes, cancer, ulcers, and anxiety. Dua et al. (2021) found myricitrin, a glycosyloxyflavone in *Myrica esculenta* bark, ameliorates diabetic nephropathy reducing oxidative stress and suppressing inflammation, suggesting it is a potential therapeutic agent for diabetic nephropathy. *Acacia catechu* (L.f.) Willd is a deciduous tree with bioactive secondary metabolites to be used for the formulation of pharmaceutical products. Besides different therapeutic values, *A. catechu* bark extract showed cytotoxic activity useful for oral cancer (Lakshmi et al. 2017; Aryal et al. 2021). Juglone

Table 2. Tree bark utilization in Nepal.

Tree species	Current distribution in Nepal	Parts that can be utilized	Growing elevation	Utilization	Active constituents	References
Acacia catechu (L.f.) Willd	Lower mountains and hills	Bark	≤1400 m	Hepatoprotective	Catechin, epicatechin, and flavonoids	Lakshmi et al. 2017; Aryal et al. 2021
Azadirachta indica A. Juss.	Terai regions	Leaves, stem, bark	≤900 m	Fertilizer, biopesticides	Azadirachtin, nimbolinin	Karki and Karki 1993; Sarkar et al. 2022
Cinnamomum zeylanicum Breyne	Mid hills	Leaf and bark	450–2000 m	Spice and flavor for food	Cinnamaldehyde and eugenol	Sathishkumar et al. 2009; Sharma et al. 2016
Juglans regia L.	Mountain ranges	Bark	1000–4000 m	Dyeing	Juglone	Ali Khan et al. 2016; Bukhari et al. 2017; Dhruba Bijaya et al. 2021
Myrica esculenta Buch.-Ham. ex D. Don	Throughout the mid-Himalayas	Bark	1300–2100 m	Antiasthmatic analgesic anthelmintic activity	Flavonoids	Kabra et al. 2019; Dua et al. 2021
Persea odoratissima (Nees) Kosterm.	Mid and far western	Bark, leaves	1000–2500 m	Antioxidant and antimicrobial	Phenolic contain, total flavonoid	Pyakurel et al. 2018
Phyllanthus emblica L.	Midhills	Bark	100–1600 m	Antioxidant	Phenols, total flavonoids	Chaphalkar et al. 2017
Pinus roxburghii Sarg.	Sub-tropical region	Bark	1200–2100 m	Anti-microbial and cytotoxic activity	Friedelin, ceryl alcohol and β sitosterol	Satyal et al. 2013
Pterocarpus				*marsupium* Roxb.	Naturally distributed in the foothills of Siwalik	Leaf, bark
150–1100 m	Diuretics, tongue diseases, chronic ulcers	Flavonoids and polyphenol	Pant et al. 2017; DoF 2018			
Zanthoxylum aramatum DC. (syn Z. alatum Roxb.)	Mid-hills	Leaves, fruits, stem, bark	1000–2500 m	Deodorant, disinfectant and antiseptic	Alkaloids, flavonoids	Phuyal et al. 2019

is the main color constituent in *Juglans regia* L., which is used as a dye in wool fibers (Ali Khan et al. 2016). Bukhari et al. (2017) investigated the influence of metallic salt mordants on the dyeing characteristic of wool fibers using *J. regia* L. bark extract showing good to very good light fastness ratings. This showed that dye obtained from *J. regia* L. bark has the potential of being utilized in the textile dyeing industry.

4. Future perspectives

The determination of the biological activity of chemicals present in tree barks is a critical process as the extraction of compounds varies between species and should be commercially viable. Also, the extraction methods influence the yield and quality of the extracted compounds and their subsequent processing. Extracting specific chemicals from biomass may be done using a variety of methods. Supercritical extraction with CO_2 is one of the most essential extraction procedures since the extract obtained contains no solvent and so does not require any solvent removal. Research on new methods dealing with extraction efficiency, biodegradability, recyclability, and lower price is needed. This asked many researchers and companies about the development of green technologies and products. Despite the efforts of numerous researchers, isolating specific chemicals from extracts in desirable quality and quantity without compromising their biological activity remains a major difficulty. There are some bio-based adhesives (Bona R851 (wood floor adhesive), 3 M super (adhesion on different applications), Bioglue, FocalSeal® (to avoid air leakage in lung surgery), DuraSeal® (spine and Dura sealing), Coseal® (for preventing the leakage of blood vessels) available in the market produced by pharmaceutical and wood industries, but one bio-adhesive never fits all the applications. Therefore, techno-economic analysis and assessment of the environmental profile associated with the production of bio-adhesive are necessary.

5. Conclusion

Tree bark is a readily available biological raw material with a unique chemical composition that has been utilized as natural raw material for centuries. With time development of technology in the scientific sector, the utilization of the product increases in different sectors. Moreover, the increase in people's demand for natural and green products gains significant attention. The bark extract is utilized as a green chemical and used for the treatment of different diseases. Rich tannin composition in bark helps to make it an environmentally safe and high-quality adhesive for the forest industry. Also, tree bark extract has antioxidant and antibacterial properties; therefore, the pharmaceutical and food industry are showing interest. However, variation in the chemical makeup of bark among tree species makes it difficult to develop a universal procedure for bark valorization. Therefore, more research is needed to be done taking into consideration the rapid development of the bio-adhesive market and environmental and economical values.

Author contributions

Sudip Pandey conceived and designed the manuscript. Sudip Pandey and Poonam Pant wrote the manuscript and contributed equally.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data presented in this study are available on request from the corresponding author.

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