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Review

Shellac as a multifunctional biopolymer: A review on properties, applications and future potential

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ABSTRACT

Shellac is a physically refined form of lac resin, a natural biopolymer of animal origin obtained from tiny insects feeding on the sap of specific host trees. Shellac, in its basic form, is a polyester macromolecule composed of inter and intra esters of polyhydroxy aliphatic and sesquiterpene acids. It has been used in several industries for ages due to its exceptional properties such as film-forming, adhering, bonding, thermoplasticity, water-resistance and easy solubility in spirit and aqueous alkali solvents. From the beginning of the 21st century, due to increasing demand for natural products, a paradigm shift in the scope and applications of shellac has been witnessed, especially in green electronics, 3D printing, stealth technology, intelligent sensors, food and pharmaceutical industries. Shellac offers enormous potential for greener technologies as a natural and environmentally friendly material. This review provides an insight into the lac in detail, covering various forms of the lac, structure, properties, different applications of shellac and its future potential. This article would benefit the researchers involved in shellac research and others looking for natural and greener alternatives to synthetic polymers in various applications.

1. Introduction

The word “lac” originated from the Sanskrit word *Laksha*, meaning a hundred thousand and refers to many insects that cover twigs of host trees and are involved in its production [1–3]. Lac is the only insect originated natural resin obtained from lac insects, mainly *Kerria* spp. (Family-Tachardiidae, order-Homoptera). The commercial host plants for these insects are palash (*Butea monosperma*), ber (*Ziziphus mauritiana*), kusum (*schleichera oleosa*) and semialata (*Flemingia semialata*) [4–8]. The lac insects settle on the tender shoots of these host plants, feed on their sap and complete their life cycle, during which female insects secrete a resinous protective coating around their body, which is harvested as a lac crop (Fig. 1). Lac insect is found in India, Thailand, and Myanmar in a large area and limited area in other countries of Asia [9,10], but in abundance, it occurs only in India and Thailand.

Lac has been used in India for centuries as a source of red colored dye and decorative coatings, having its mention in the Atharva Veda, ancient holy literature in India composed during 1200–900 BCE [2,11,12]. Historical records from the 12th to 16th centuries indicate that lac was used to decorate public buildings, waxing lemon and oranges, finish furniture, wood polishing, and repair broken pottery and jewellery in China, Europe and India. However, the first export of lac dye to Europe was in 1607, which flourished until the 19th century with the advent of aniline dyes. After that, the lac resin was taken up for export, especially in the gramophone industry, varnishes, medicines, etc. The use of lac is now diversified in many fields [13]. However, despite the many benefits of lac, the availability of synthetic alternatives at cheaper rates led to a decline in the demand for lac in non-food application areas. Nevertheless, in recent times, due to the increasing awareness of the people towards the natural products, lac and lac-based products are again in high demand worldwide.

In today's context, lac is a good source of income for people depending on forest products for their livelihood. It also provides employment opportunities, mainly in the off-agriculture seasons [14]. Due to its natural, non-toxic, biodegradable, eco-friendly nature, lac has been in consistent demand in the market, and hence its farming or

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cultivation has been a profitable business [15]. Shellac, a refined lac product, has been permitted as a food additive by the European Union (EU) with E number E904 and has also received a GRAS (Generally Recognized As Safe) status from the U.S. FDA [16]. For quality control of shellac in India, the standard protocol given by the Bureau of Indian standard IS: 6921 – 1973 [17] describes various processes for test and analysis. To support the medical, pharmaceutical, and tissue engineering applications of shellac, its biocompatibility [18,19], biodegradability [20–24], cell compatibility [25–28] and toxicity studies [16,29–31] are already established. The effect of the topical application of shellac on the skin was studied [32] and found to have no irritation. Shellac based varnish was found to have superb cell compatibility [29], and its solution also showed a capacity to embolize gangrenous tissue [33]. Less than 10 % digestibility of shellac in gastric and intestinal fluids was reported [34], indicating that shellac can act as a dietary fibre. Considering the possibility of shellac producing hydrolysates in the intestine, bioactivities of sesquiterpene components were studied by cytotoxicity and antibacterial tests [35]. No component exhibited cell growth inhibition activity which proved shellac as a safe material for formulations to be consumed. Further studies on the biological activities of shellolic ester components [36] indicated that the shellac is edible, physiologically non-toxic and can be safely used as a non-toxic material in food, pharmaceuticals and other industries at the level employed as an excipient. The complete biodegradation of pure shellac resin is yet not investigated exhaustively except few studies which indicate the molecular changes during ageing. A study by Sarkar and Srivastava reported the possibility of hydroperoxidation and inter-etherification reactions during the thermal and UV degradation of shellac [37]. Ghoshal and coworkers revealed faster degradation of the shellac films when grafted with hydrophilic monomers such as 2-hydroxyethyl methacrylate [38].

Owing to its unique properties, it finds extensive applications in food [39–44] and pharmaceutical industries [45–47]. Hence, lac and its value-added products are exported to various places globally. Resin, dye, and wax are three major and commercially important components of raw lac. Lac dye is a commercially important byproduct of the lac processing industry known as Natural Red 25 (CI Number 75450) in international trade [48]. With at least five laccaic acids (A, B, C, D and E) as its principal constituent, this natural dye has multiple applications in the food, pharmaceutical, cosmetics, and textile industries [49]. Also, a variety of lac-based products and byproducts, including seedlac, shellac, button lac, aleuritic acid, isoambrettolide, lac wax, bleached lac and dewaxed decolorized lac (DDL), are obtained by processing and value addition of lac and find a great demand in the international market. Thus, it has enormous applications in industries like food, pharmaceuticals, cosmetics, perfumes, varnishes, paints, polishes, adhesives, jewellery and textile dyes [7].

Though many industrial applications of shellac have been studied, there is an immense potential to use this fabulous material for advanced applications as a replacement for its synthetic counterparts. Very few reviews [8,45–47] are available describing shellac, and some focus on its food applications [39–44,50–53]. However, no review is available that critically discusses the properties in detail and diverse applications, including their non-food applications and future potential. This review discusses an overview of shellac's source, chemistry, and properties and its applications in various industries like food, pharmaceuticals, coatings, paints and varnish, polishes, adhesives, cements, electronics, and other modern industries technological innovations.

1.1. Production statistics in India

According to the survey conducted by Natural Resins and Gums Cell, ICAR-Indian Institute of Natural Resins and Gums, Ranchi, India, the production of sticklac in India during 2020–21 is 21,740 tons. Jharkhand ranks first among lac growing states in India, followed by Chhattisgarh, Madhya Pradesh, West Bengal, Maharashtra and Odisha [7,54,55]. Together, these six states contribute >98 % of the national production [8,55]. The contribution of Jharkhand to national lac production is about 55 %, followed by Chhattisgarh (16 %), Madhya Pradesh (14 %), West Bengal (6 %), Maharashtra (5 %) and Odisha (2 %).

Need of a favourable range of temperature, humidity, rainfall, and a threat from the enemy insects, yield from lac crop is highly dependent on abiotic and biotic factors. It is not only influenced by the climatic factors affecting the insect directly but also its host tree indirectly [56]. The risk of crop failure is high in the season having adverse climate, as observed during the year 2010–11, when lac production in India was minimum, as shown in Fig. 2. During the last two decades, the average production of lac in India was 18,385 tons, with the highest production of 23,239 tons recorded during 2006–07. Although lots of fluctuations in the overall production are seen, recently, due to the adoption of lac production on cultivable, bushy host i.e., Flemingia semialata, by the farmers, an increasing trend in the production has been observed from 2017-18 onwards (Fig. 2). *F. semialata* being a small-sized host plant, can be cultivated in fields like other crops and becomes ready for lac

Fig. 1. Lac growth on host plant (A. Insect settlement, B. Intermediate stage and C. Mature crop).

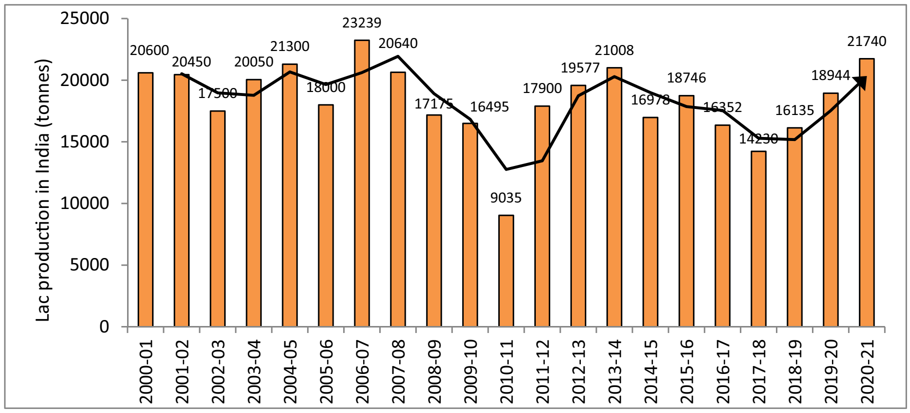

Fig. 2. Trends in lac production in India.

cultivation in one year, whereas for a large tree host, one has to wait for 5 to 10 years. Also, due to the small size of semialata, lac culture operations like pruning, inoculation, spraying, and harvesting can be performed even by women farmers as climbing a tree is not required.

1.2. Export

Lac is produced mostly in Asian countries but is being consumed and imported almost all over the world. Major global producers and importers of the lac and its value-added products are depicted in Fig. 3. The export of lac and its value-added products (shellac, aleuritic acid, seedlac, de-waxed shellac, bleached lac, shellac wax, button lac and gasket lac) during 2020–21 from India was 7692 tons with a value of >75 million dollars (Fig. 4). Roots of instability in export values of lac, especially during 2011 to 2014 with its peak touching 75 M$ during 2013–14, go to unpredicted drop in production, almost half of the average, in the year 2010–11. The drastic reduction in export during 2012–13 created panic in the lac-based industry about its short supply in the future from India. This resulted in the sudden rise in the price of lac and its products, which again stabilized due to consistency in production from 2013 onwards. Since then, a steady increase in the demand and value of NRGs has been observed in the international market. The export value-wise share of different lac-based products is depicted in Supplementary Fig. 1. These products were exported to various countries, including - USA (37.25 %), Bangladesh (9.54 %), Germany (7.34 %), Korea Rp (5.53 %), Afghanistan (5.45 %), Iraq (4.84 %), UK (2.63 %), Egypt (2.47 %), Pakistan (2.31 %), Spain (2.01 %), China (1.97 %), Japan (1.93 %), Indonesia (1.89 %), France (1.84 %), Thailand (1.56 %), Italy (1.54 %), Sri Lanka (1.12 %), Australia (1.10 %) and Iran (1.02 %). Globally, Indian lac is reported for its export to 76 countries in Europe, America, Asia, Africa and Australia continents [57]. The future prediction of the lac sector revealed that about 7500–8000 tons of lac and its value-added products would be required to meet the overseas demand worth 80–90 US million dollars.

2. Different forms of lac

Unlike other biopolymers, lac is found in the various forms used and preferred for different applications. Raw lac, after harvesting, undergoes a set of processing operations through which its further refined forms are obtained, as shown in Fig. 5.

2.1. Sticklac

After the twigs are cut from the lac host trees, the lac encrustation is removed from them with the help of a knife, sickle or a lac scraper

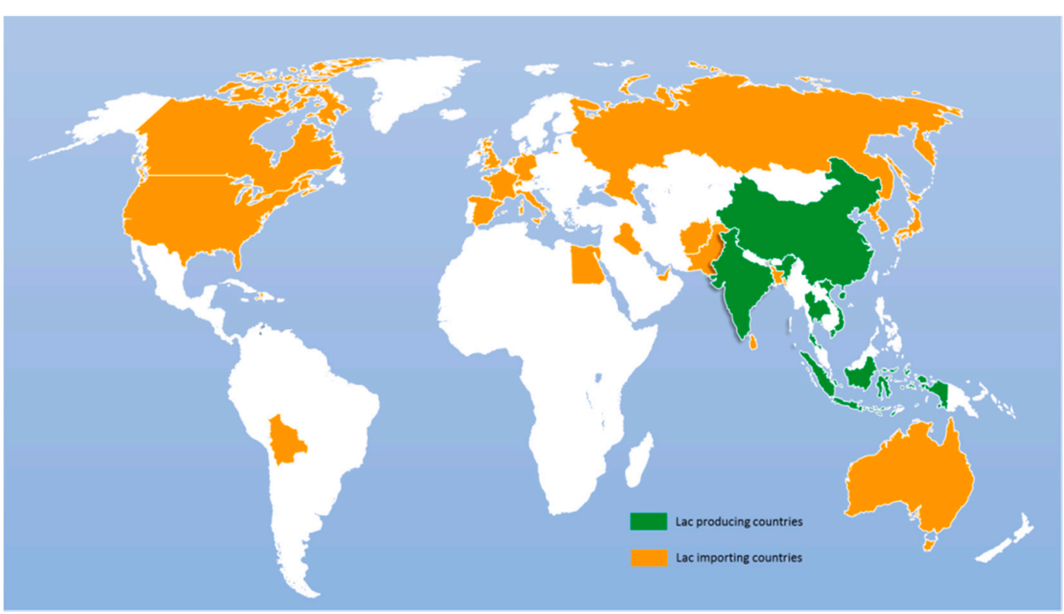

Fig. 3. Major lac producing and importing countries of the world.

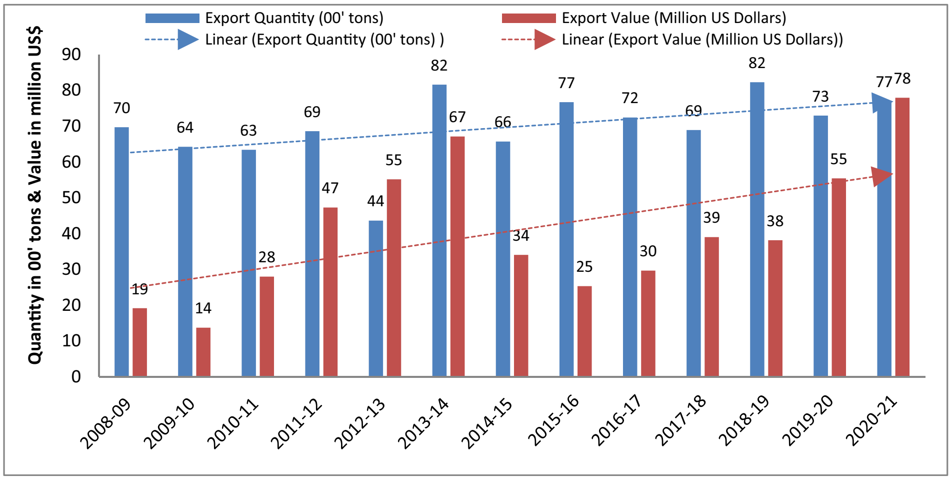

Fig. 4. Trends in quantity and export value of lac and its value-added products from India.

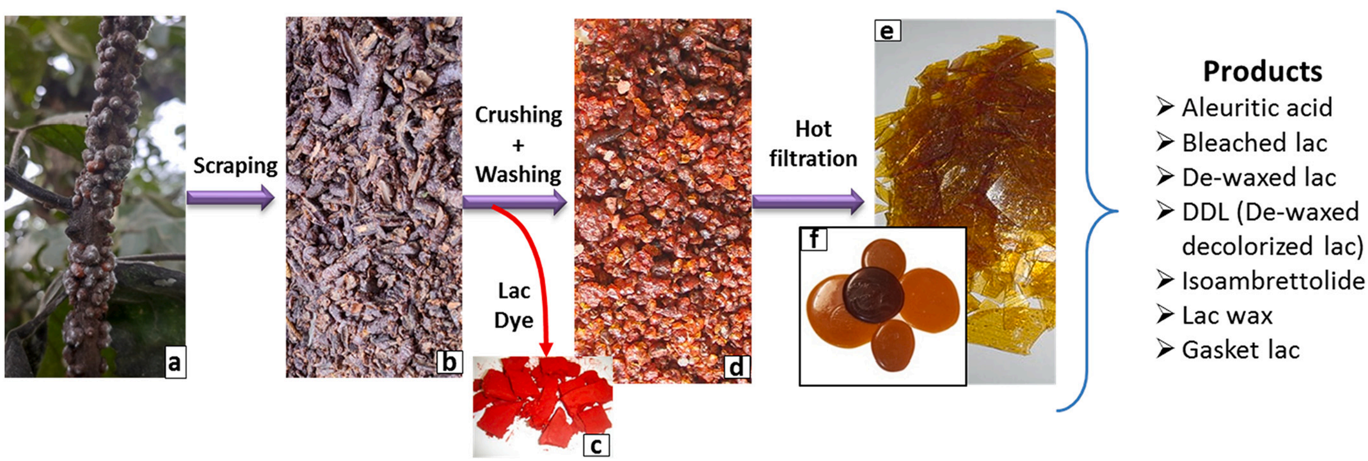

Fig. 5. Processing of lac: (a) Lac on host plant, (b) Scraped lac, (c) Lac dye, (d) Seedlac, (e) Shellac and (f) Button lac and other products (value-added) obtained from lac.

[58,59]. Thus, gathered lac is known as scrapedlac or sticklac. This crude lac contains resin, encrusted insect body, wax, lac dye, and other impurities. Its quality depends on many factors like harvesting before or after the larval emergence, the climate it is receiving, the host tree used, and the method used for drying or storing. Because it contains much moisture, it becomes necessary to dry or store it properly in the open air. However, when this sticklac is processed to obtain seedlac, it can be easily stored for a long time without loss of quality [60].

2.2. Seedlac

The sticklac contains about 30–40 % impurity, which is removed in the primary processing of lac involving five unit operations, i.e. crushing, washing, drying, cleaning and grading. For purification, the sticklac is crushed, sieved with the help of a fine sieve to clean sand and other impurities and then washed with water. Twigs, wood chips, uncrushed lac cells and other materials float on the water and can be separated easily. Lac grains are rubbed to remove any remaining water-soluble impurities. After washing, the workers carefully separate the (1) *ghunghi*, which contains uncrushed lac cells and other impurities floating on the surface of the water; (2) *pathi*, which primarily consists of insect debris and fibrous materials; (3) *molamma*, the fine lac dust that is found over the large lac grains and (4) *seedlac*, which settles at the bottom and contains large lac grains [11]. In large factories, the washing operation and separating process of impurities of seedlac is carried out with the help of machines. In lac processing factories, the seedlac obtained is often polished with oxalic acid to increase the shine and lighten the color of seedlac [61]. This is generally done by treating seedlac with a 5 % oxalic acid solution, where 1 L solution is sufficient to treat 20 Kg seedlac. The seedlac thus obtained contains 3–5 % impurity and is used as raw material for making several lac-based value-added products. In order to make seedlac at the village level, ICAR-IINRG, Ranchi, India, has developed a Small Scale Processing Unit (capacity – 100 kg sticklac/day) consisting of four machines, i.e. crusher, washer, grader and winnower. The unit can be driven manually or by an electric motor [62].

2.3. Buttonlac

The impurity present in seedlac is removed by hot filtration using an oven (*Bhatta*). Filtered molten seedlac resin is dropped in small quantities on smooth metal sheets such as galvanized iron and allowed to solidify as a disc or button of 6 to 7.5 cm diameter and about 0.5 cm thick [11].

2.4. Shellac

Seedlac is a semi-refined product processed to make shellac by using any of three methods [11].

2.4.1. By heat process

Seedlac is melted by steam heat in this manufacturing process. Molten lac is pressed through a filter with the help of hydraulic force in a hydraulic press. This filtered lac is then stretched into long sheets with the help of a sheeting roller, and then the sheets are fragmented into small flakes known as machine-made shellac [8].

2.4.2. By solvent extraction

In this process, the seedlac is dissolved in a cold or hot solvent (usually alcohol), and the insoluble residue is left to settle and then filtered [63]. The solvents are then distilled off, and the remaining molten shellac is stretched with the help of a sheeting roller. The solvent can be reused after rectification. Ordinary wax containing shellac is made using hot alcohol, and by using cold alcohol, dewaxed shellac is formed because lac waxes are insoluble in cold alcohol. If decolorization of the refined lac is required, the alcoholic extract is treated with a suitable decolorizing agent before distilling off the solvent.

2.4.3. Country process (Bhatta process)

The country process is a traditional and utterly manual method. In this process, the seedlac is stuffed into a long cloth bag (approximately 10 m long and 5–7.5 cm in diameter) then the filled bag is heated, portion-wise, in an oven containing charcoal fire [61]. One end of the bag is kept near the oven, and the other is continuously twisted manually. Lac resin and associated wax melt due to heat, and twisting pressure cause molten lac to get squeezed out from a cloth bag. The squeezed out lac is scraped from the bag's surface with the help of a spatula and mixed with water to offset any thermal effect of the fused resin. When a sufficient amount of well-mixed resin is collected, it is then transferred to a hot water container to maintain it in molten form. This molten material is spread in the form of a sheet and stretched manually with due care to achieve uniform thickness and gloss [63]. The sheet formed is then left to cool and broken into small flakes when it becomes brittle. This whole process of making shellac requires skilled human resources [9].

2.5. Bleached lac

The natural lac resin appears yellowish or brownish because of some alcohol-soluble anthraquinone pigments, including desoxyerythrolaccin, erythrolaccin and isoerythrolaccin. These pigments are supposed to be derived from laccaic acid D through a biosynthetic pathway within the insect body [64]. The color of lac may vary from yellow to dark red-brown, depending on the quantity of these pigments secreted by the insect, which has to be genetic. This color of lac resin is not desired in some surface coating applications, and hence it is removed using different bleaching agents. Gaseous chlorine, sodium chlorite, nascent chlorine, or sodium hypochlorite are used as bleaching agents for making bleached lac, but sodium hypochlorite is the most commonly used bleach commercially [61]. Chemically, bleaching is achieved by chlorination or oxidation of the unsaturation present in the erythrolaccin pigment through the action of bleaching agents. The seedlac is dissolved in hot water containing anhydrous sodium bicarbonate. Insoluble substances are removed by filtration, and the filtrate is diluted. Then sodium hypochlorite solution is added to it to start the bleaching process, and again a small portion of bleach liquor is added after consumption of added chlorine until the bleaching is complete. This whole process of bleaching takes <8 h. The bleached solution is then diluted and cooled. The bleached lac is then precipitated with the addition of dilute sulfuric acid. The precipitate is filtered and washed with cold water until the sulfuric acid and inorganic salts are removed. After this treatment, the wet bleached lac is spread on muslin cloth for drying. The yield of bleached lac is 85–90 % of the seedlac used. The bleached lac thus obtained contains the wax known as "Regular bleached lac". For refined and wax-free lac, the wax is removed after the bleaching operation or from the carbonate solution of seedlac [11].

2.6. Kiri and garnet lac

The impurities accumulated in the long cloth bags of the country process of making button lac/handmade shellac also comprise a good amount of lac. When this material is collected in sufficient quantity, the cylindrical bag is slit opened with the help of a knife, and the semi-molten mass is cut into circular slabs of 10–15 cm in diameter and 2.5 cm thick. This byproduct is known as "*kiri* or *kirilac*", which contains about 50 % lac [61,63]. Lac can be reclaimed using the solvent extraction method. This lac is known as garnet lac [11]. The small amount of lac still adhering to the used cloth bag is recovered by hot water, and the lac thus obtained is known as *passewa* which is inferior grade shellac.

3. Chemical structure

Being produced from a living organism having a unique system in its body to produce lac, the chemical structure of lac resin is a bit complex with finer variations in the proportion of its components. In its natural form, Shellac is a long chain polyester type of resin consisting of inter and intra esters of polyhydroxy carboxylic acids where some acids are aliphatic long-chain hydroxy acids, and some are sesquiterpene acids [65,66]. Pioneering work on revealing the typical structure of this complex biopolymer was done during the 1960s at National Chemical Laboratory, Pune, India, which was published through a series of literature in seven different parts [67–73]. Further confirmation of this structure and molecular characterization of the constituent acids was done using pyrolysis-GC [64] and recently, flow injection-LC, electrospray ionisation and MS [74]. The shellac is a composite macromolecule with a combination of hard and soft resin as significant components, along with wax and other odoriferous principles. Although the shellac consists of several polyester species naturally bound together with the complex linkages [75,76], a typically isolated fraction with a homogeneous nature, called pure lac resin, was studied and was also termed as a backbone of the shellac molecule [69]. Out of the aliphatic acid components of shellac, the most abundantly found member is aleuritic acid (approx. 35 %), whereas jalaric acid, with approximately 25 % share, is the most crucial member of terpenic acids. Other acids isolated are butolic (~8 %), shellolic-epishellolic and laccijalaric (~8 %) acids [76]. A typical unit of shellac (Fig. 6) is supposed to have a whole five hydroxyl groups, one free carboxyl group, three ester groups, a single partially hidden aldehydic group and an unsaturation with a double bond in one place. These functional groups are chemically bound together with ester, acylal, acetal and ether linkages [76]. The material is amphiphilic in nature where hydrophilicity is imparted by the free carboxylic part of the sesquiterpene acids and aliphatic long chain hydroxy acids are responsible for its hydrophobicity (Fig. 6). This property of lac makes it suitable for a variety of applications where the orientation of molecules plays a significant role.

4. Physical and chemical properties

Shellac is a hard, brittle resinous solid. Its color can range from light yellow to dark red. It is odourless in cold conditions, but it smells when heated.

4.1. Solubility

Shellac is associated with coloring matter (0.5–1.0 %), odoriferous principles, wax (4.5–5.5 %), resin (90–94 %), moisture (1–2 %), insect debris and other extraneous matter (0.5–4 %). The partial solubility of shellac in ether was studied [77], and this property was used to separate hard/pure (the portion which is insoluble in ether) and soft (the portion which is soluble in ether) resin. The solubility of shellac in acetic acid, ethyl and methyl alcohols, caustic soda, sodium carbonate, borax solutions and its partial solubility in ethyl acetate, ether, chloroform, carbon disulphide and acetone were also reported. The shellac is insoluble in

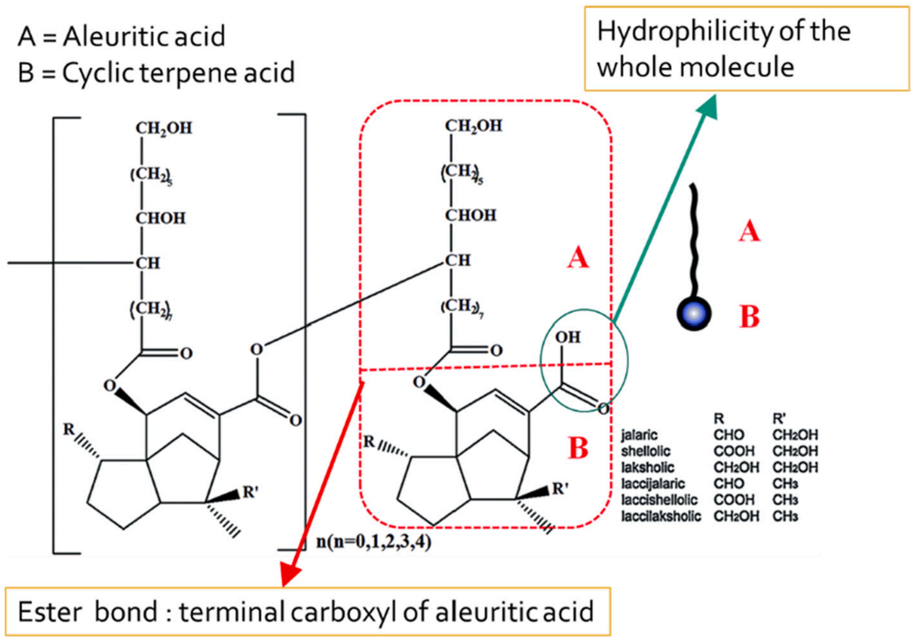

Fig. 6. Chemical structure of the typical building block of shellac.

petroleum ether, benzene and toluene. After many studies, it was found that the best solvent for shellac is alcohol, organic acid and ketones [11]. Different classes of solubility of shellac in various solvents are given in Table 1.

4.1.1. Solubility in mixed solvents

The best and most precise compositions for dissolving shellac are acetone containing 5–10 % water and other polar substances, such as alcohols, acids, and methyl acetate diluted with an equal amount of glycol [78].

Table 1
Solubility of shellac in various organic solvents.

Solubility of shellac	Solvents
Highly soluble	Pyridine
Soluble	Acetaldehyde, acetic acid, Amyl alcohol, aniline, isobutyl alcohol, n-butyl alcohol, s-butyl alcohol, ter-butyl alcohol, isobutyl carbinol, sec-butyl carbinol, diethylcarbinol, diacetone alcohol, diethylene glycol, diethylene glycol butyl ether, diethylene glycol ethyl ether, diethylene glycol methyl ether, ethyl alcohol (anhydrous), ethyl alcohol (95 %), ethyl lactate, ethylene glycol butyl ether, ethylene glycol ethyl ether, ethylene glycol methyl ether, formic acid (85 %), Fusel oil (refined), methyl alcohol, methyl propyl carbinol, propionic acid, isopropyl alcohol, propylene glycol+ ethyl ether (mixture), propylene glycol + methyl ether (mixture), propylene glycol, mesityl oxide, monomethyl aniline
Fairly soluble	Acetone, acetophenone, butyric acid, cyclohexanes, dimethyl ethyl carbinol, ethyl acetate (85 %), ethyl methyl ketone, ethyl oxybutyrate, ethylene glycol ethyl ether(commercial), lactic acid, propylene glycol
Slightly soluble	n-butyl acetate 85 %, citronellol diethyl ether, ethyl aceto-acetone, geraniol
Insoluble	Amyl acetate, Amyl chloride, benzene, bromobenzene, butyraldehyde, n-butyl acetate pure, isobutyl propionate, carbon disulphide, carbon tetrachloride, chloroform, dibutyl phthalate, diethyl aniline, diethyl carbonate, diethyl phthalate, dimethyl aniline, ethyl acetate(pure), ethyl oxalate, ethyl sulphate, ethylene dichloride, ethylene glycol, ethylene glycol ethyl ether acetate (distilled), glycerol, palmitic acid, petroleum ether, toluene, xylene, nitrobenzene
Swells	Chloroform, ethylene dichloride, toluene, xylene, nitrobenzene

4.1.2. Solubility of shellac in alkaline solutions

Shellac is insoluble in water, but it dissolves in alkaline solutions when cooled due to its acidic nature. On heating, it forms solutions of alkaline salts such as sodium carbonate, borax and organic bases (triethanolamine, morpholine), etc. Proper salt formation occurs with sodium carbonate and bicarbonate because free CO_2 has been observed to correspond to the acid value [79]. Shellac behaves like a colloid in dilute aqueous solutions. The hydrosol of shellac can be easily prepared by continuously adding alcoholic solutions to water and evaporating the alcohol in a vacuum. Aqueous alkaline shellac solutions have a higher viscosity than alcoholic solutions of the same concentration [11].

4.2. Softening and melting points

Shellac has no sharp softening and melting point like other resins. However, according to the Indian Lac Research Institute study, the softening point of shellac is between 65 and 70°' and the melting point is 10° higher than that. According to Sharma and coworkers, when dewaxed shellac is heated gradually, it softens at 65–70 °C and melts at 75–80 °C [76].

4.3. Specific gravity

Specific gravity values of shellac at 15 °C temperature were found in the range of 1.035–1.114 [80].

4.4. Refractive index

Bhattacharya, in 1940, measured the refractive index with an Abbe refractometer at different temperatures [81]. According to him, the refractive index of shellac is 1.5272. He also stated that the exact temperature for the refractive index determination of shellac is 70 °C because this temperature is close to the melting point of shellac.

4.5. Specific heat and heat of fusion

Srivastava, in 1957 reported that the specific heat of *kusmi* shellac was found to be 0.33–0.39 Cal/cm.°C in the temperature range of 20–35 °C [82]. The maximum value (0.71) was found in 70–75 °C temperature. On calculating the heat of fusion, it is 12.6 cal/g.

4.6. Optical properties

If the color of shellac is from translucent pale orange to opaque dark red, then it is considered more important because it gets a higher price. Usually, a solution of shellac dissolved in alcohol is matched to an iodine solution by colorimeter or transmitted light for absolute value. Lac gives orange-red fluorescence in ultraviolet light. Lac does not degrade quickly and possesses good transmission characteristics with stability towards yellowing under the influence of ultraviolet light [34].

4.7. Acid value and saponification value

Shellac undergoes continuous esterification induced polymerization with ageing resulting in the consumption of its acidic functional groups. These changes can be studied by estimating their acid value, which is an excellent indicator of the quality or condition of lac samples. Lac with a higher range of acid value often fetches better prices in the trade as with time, and during storage, the acid value keeps decreasing continuously [84,85]. The acid value of shellac ranges from 60 to 65, as reported by most investigators [11]. Still, some reporters have observed acid values in the range of 65 to 75 [76]. Also, when lac is refluxed with 0.5 N alkalis for 2 h, its accurate saponification value can be found. Accordingly, the saponification value of lac is reported as 225–230 [86].

4.8. Basicity and iodine value

Pure resin shellac has a basicity of 2, and soft resin shellac has a basicity of 1. According to Wij's method, the iodine value of shellac ranges from 14 to 18 [87].

4.9. Molecular weight

Numerous workers have attempted to estimate the molecular weight of the various fractions of shellac in the past using different methods such as dioxane, osmotic pressure data, GLC, and still, no unanimous opinion has been achieved. Several values are reported for the molecular weight of the two different components of shellac, such as 2210 [73], 2000 [88] for the hard resin (ether insoluble portion) and 550 [88], 500 [11] for the soft resin (ether soluble portion); whereas, for practical purposes, the average molecular weight of shellac is considered to be 1000 to 1006 [11,89]. Nevertheless, it is opined that the characterization of the macromolecular structure of shellac as such is not possible in GC–MS or other methodology, as it requires saponification or pyrolysis or solvent extraction pre-treatments [90]. Recently, Bar and Bianco-Peled in 2021 used Flow Injection Analysis - Electrospray Ionisation - Quadrupole-Time of Flight (FIA-ESI-Q-ToF) technique by injecting the complete shellac sample to achieve greater accuracy in the characterization of shellac [91]. They identified a variety of combinations of compounds found in shellac, summation of the average molecular weights of all these components is at least 5800. Another study published in Nature Scientific Reports elaborately highlighted the molecular fragmentations of shellac by HPLC-ESI-Q-ToF [74]. They reported the shellac as a combination of free acids, esters, di, tri, tetra, penta, hexa, and heptaesters made up of the building block of hydroxyl-aliphatic and sesquiterpenic acids. Combined molecular weight of these building blocks is >62,000. Moreover, with ageing shellac undergoes self-esterification or polymerization as a result of cross-linking of its components [90]. The molecular weight of shellac in the case of such cross-linking increases manifold.

The different properties of shellac reported in the literature are summarized in Table 2.

4.10. Other properties

Shellac is characterized as a semi-crystalline polymer that is less regularly aligned, brittle, and less dense. It behaves as a polycrystalline material, having a smaller crystallite size on a 1 nm scale. Crystallization of shellac is time and temperature controlled as it decreases with lowering temperature after melting it at 90 °C and depends on the cooling rate. X-ray diffraction (XRD) analysis of shellac gives two sharp signifying crystalline regions and one broad peak, signifying shellac's amorphous section [92].

In a typical FTIR spectrum of shellac, some familiar characteristic peaks for the major functional groups are observed [87]. These peaks include a broad peak in the range of 3600–3200 cm^{-1} for the —OH vibrations from acidic and hydroxyl functional groups, a sharp peak or couplet at 2940–2840 cm^{-1} attributing to the —CH stretching and a sharp peak rather a shouldered sharp peak at around 1750 to 1650 cm^{-1} representing the C═O band from acid and shoulder for the C═O of ester group [93]. Differential scanning calorimetry (DSC) analysis of shellac

Table 2
Physical, electrical and chemical properties of shellac.

Sl. no.	Physical properties		Electrical properties		Chemical properties		Thermal and mechanical properties	
1.	Specific gravity	1.14–1.2	Dielectric constant (30 °C)	2.73 - 3.91	Acid value	65–75	Softening temperature	65–70 °C
2.	Refractive index	1.521–1.527	Dissipation factor (30 °C, 50 Hz)	0.0051	Saponification value	220–230	Melting temperature	77–90 °C
3.	Specific heat at 10–40 °C	0.36–0.38 Cal/cm.°C	Dielectric loss (30 °C, 50 Hz)	0.026	Ester value	155–165	Glass transition temperature	38–40 °C
4.	Specific heat at 45–50 °C	0.3 - 0.6 Cal/g.°C	Dielectric strength (kV/mm)	14 - 40	Hydroxyl number	250–280	Time of polymerization at 150 °C / Life under heat	30–120 min
5.	Melt viscosity (Poise)	22,505 (@80 °C) 2154 (@95 °C)	Volume resistivity (Ohm cm)	1.2 - 262 $\times 10^{13}$	Iodine number	14–18 (Wij's) 8–12 (Hubl's) 23–25 (By H absorption)	Storage modulus (MPa)	0.001 - 0.1
6.	Thermal conductivity (@30 °C)	0.0024 - 0.0025 (W/cm.°C)	Surface resistivity (Ohm cm)	0.4 - 175 x 10^{13}	Carbonyl value	7.8–27.5 (Sod. Sulphite method)	Ultimate tensile strength at 20 °C (MPa)	10 - 14
7.	Molecular weight	2000–2210 (Hard resin) 500–550 (Soft resin) 1000–1006 (Average)	Thiocyanogen number	18 – 20	Absorption maxima in ethanol solution (nm)	225, 285, 425	Abrasion resistance (sand)	110
8.	Flow (ASTM)	45–100 mm	Optical rotation	+ 54 to + 64	IR peak positions (cm^{-1})	3448 (—OH) 1680 (—COOH) 725 (—C═C—)	Scratch hardness (1 mm ball on copper)	4.5–5.5 Kg

also confirms its semi-crystalline nature, with glass transition temperature in the range of 40 to 50 °C. Shellac behaves like a hard, brittle and amorphous material below its glass transition temperature, whereas above this temperature, it is converted into a soft flowable and thermoplastic material [94].

4.11. Ageing or polymerization of shellac

Shellac undergoes ageing, which is chemically its self-esterification or polymerization. As most of the acid components of shellac have hydroxyl groups, too, with time, gradual self-esterification results in a drop in acid value, reduced solubility and a rise in the glass transition temperature and brittleness [85]. Gas chromatography, HPLC, and mass spectra studies reveal monomer crosslinking of the polyester matrix resulting in decreased viscosity due to de-esterification of aleuritic acid from the shellac monomer [90]. This de-esterification could establish aleuritic acid as the precursor of the crosslinking mechanism. Increased concentration of newly formed esters could be the reason for decreased solubility of shellac in alcohols. The ageing of shellac occurs in a series of steps starting from the oxidation of aldehyde groups to carboxylic acid groups, which react with hydroxyl groups to form esters. In a recent study, small-angle X-ray scattering patterns of shellac nanofibers showed no significant change in its nanostructure when aged for one year as compared to freshly prepared shellac; however, few variations were seen in intensity of the peak at low q values and around $q = 2\ nm^{-1}$ [91]. Visible shellac polymerization changes include sticking individual flakes together to form blocks. Avoiding direct contact with light and storage below room temperature (27 °C) helps retain the properties for a longer duration without significant effects of ageing [95]. Treatment with small amounts of antioxidants or the formation of its ammonium or other organic salt has been found helpful in prolonging the quality of shellac [96].

4.12. Influence of host plants on the quality of lac resin

As two different strains of lac insect, *rangeeni* and *kusmi*, feed on the selective host plants (*rangeeni* specific to *B. monosperma* and *kusmi on S. oleosa*), the properties of resin produced by them differ significantly. Overall, the resin produced by *Kerria* sp. *kusmi* strain, especially on the host *S. oleosa*, is superior to its *rangeeni* strain. The properties like flow, heat polymerization time, color index, etc., were found better for *kusmi* lac compared to *rangeeni* [56]. According to Sharma et al., 2016, the resin producing potential of the lac insect depends on the type of lac host it is feeding on [97]. The average resin production of *kusmi* strain is higher than the *rangeeni* strain. Additionally, *S. oleosa* is considered the most suitable host in terms of quality and quantity of resin. For the *rangeeni* strain, lac production is highest in *B. monosperma* and *Z. mauritiana* during the summer and rainy seasons, respectively.

5. Applications

Diverse applications of shellac and lac-based products are covered in this section (Fig. 7).

5.1. Varnish, lacquer and polish formulations

Shellac has been used for centuries as a sealer, primer and lacquer [98]. By its application, the solvent evaporates, leaving a solid hard film on the wood/metal surface where it is applied [99]. A simple air drying type brush-able and spray-able varnish compositions with the help of shellac, denatured alcohol, n-butyl alcohol and plasticizers were developed in the 1940s [100]. The addition of 0.5 to 1 % of 10 % solution of sulfur monochloride in carbon tetrachloride to shellac improved the water resistance property of varnish [101]. Incorporating allyl starch into shellac increases its heat and solvent resistance property [102,103]. Melfolac was produced by mixing modified dewaxed shellac

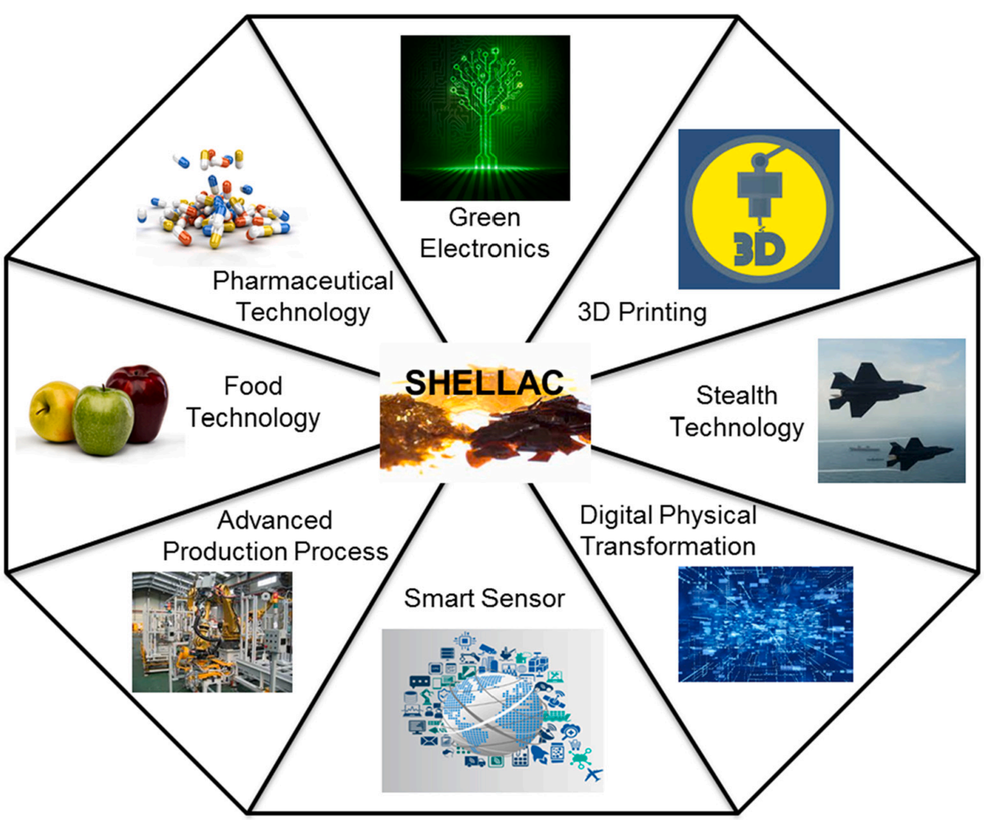

Fig. 7. Applications of shellac in modern technology.

with butylated melamine formaldehyde resin, heat and waterproof shellac varnish for wooden furniture [104]. Due to the difficulty of obtaining methylated spirit, a spiritless varnish composition is prepared with the help of shellac, which gives a smooth, glossy and attractive finish to wooden furniture [105]. With the help of shellac etch primer, a composition is prepared, which gives a smooth and highly adherent coating to aluminium and light metals. In addition to air-drying shellac varnish, oil-based varnish has also been prepared [106,107].

Further advancements in the lac based varnishes were made [108] by reaction of shellac, rosin, and zinc oxide complex in stand oil which dries within 2 h and is glossy. Another improved varnish composition was prepared from lac, linseed oil having good drying characteristics, which is stiff, glossy, smooth, flexible and shows good resistance to water and aromatic hydrocarbon solvents [109]. This varnish is pigmented and used for decorative paints and can also be prepared with the help of non-drying oils. Varnish can also be prepared from cashew nut shell liquid and shellac [110].

For making water-based coating composition, shellac is first treated with base, and then it gets dissolved in water because shellac cannot dissolve in water unless organic or inorganic bases are added to it. Shellac improves the film properties of synthetic polymers [111]. Shellac solution, which contains sodium salt of carboxylated methylcellulose, solutions of aluminium, and chromium ferric sulphate, shows good water resistance properties if the film is made from them. It does not even deteriorate in adhesion [112]. Floor polishes [113] and anti-nail-biting lacquers with bitter herbal extract [114] were also developed from shellac.

A study on heat resistant, moisture repellant lacquer was done using shellac, 10 % ammonia, leather gum, ethyl alcohol, diacetone alcohol, aldol and urea [115]. Non-inflammable fire resistant varnish from shellac for wood paper and fabrics was prepared during the late 19th and early 20th centuries [116]. Water-thinned shellac for primer steel was prepared [117]. Similarly, water thinned shellac paints for interior decoration were also prepared [118]. Aqueous solution and dispersion from high shellac content have been developed. This shellac solution and dispersion are used in the paint varnish industry, food industry and cosmetics [119]. It was reported that shellac varnish is used to protect dental pulp to avoid the harmful effects of cement filling [120].

The use of shellac has been reported in many formulations as a protective lacquer for silvering mirrors [121], for lacquering in rubber shoes [122], for self-degradable copying paper coating [123], food and confectionery coating [39,124], powder coating [125], in xerographic binder plates [126], electrography recording composition [127], jute fabrics coating [128], high gloss polishes for tiles [129]. Ammonical shellac solution is also used for electrography coating [130].

5.2. Lac in the electrical industry

Shellac has been used in electrical industries since time immemorial. The coating composition for the insulation of telegraphic wires has been developed [131]. Insulating varnishes are used for coating electric motors, transformers, finishing electrical components, micanites, and laminated products [132]. It was stated that the dielectric strength of shellac is high (62–80 kV/mm) [133]. Shellac- urea formaldehyde varnish is suitable for air-drying and baking type use. The reaction of butylated melamine and butylated urea formaldehyde of dewaxed lemon shellac can improve dielectric strength [134]. Dimethyl phthalate treated shellac varnish shows good resistance to transformer oil [135]. When shellac is incorporated into drying oil in the presence of metal oxide, it forms a solution. These solutions form cheap aromatic solvents and produce flexible films with improved dielectric properties.

Baking type shellac varnish, DL shellac was prepared by reaction of double-boiled linseed oil, lime and litharge. This varnish had good drying characteristics, compatibility with thinner, water mineral and transformer oil resistance and high dielectric strength of 84 kv/mm [136]. A process was developed to prepare shellac bond powder which can be used in laminated micanite and other micanites [137]. Similarly, many compositions were prepared from shellac. A coating composition for wood surfaces has been developed using nanostructured zinc oxide and shellac varnish, which has aesthetic and water-repellent characteristics and is resistant to decay induced by light and fungal agents [138]. Due to the good insulating properties of shellac, it is used as a high-quality dielectric layer in organic field-effect transistors [21]. Other uses include finishing varnish for field magnets [135], electric wire enamels [139], solventless lamination for mica [140], laminated insulators for oil-filled electrical devices [141,142], mica insulators for spark plugs [143], acid-resistant insulating material [144]. Shellac and graphite-based disposable electrochemical sensors for sulfamethoxazole detection were also investigated [145].

The organic field-effect transistor (OFET) is a type of transistor where an electric field controls the current flow in a semiconductor. It is a triode where three terminals are accounted for source, gate and drain [146], as shown in Fig. 8. The performance of the organic field-effect transistor significantly relies on the growth properties of the organic molecules on the gate dielectrics, the behaviour of the interface and physical processes during the device operations. High dielectric materials possess multiple advantages for the operation in OFET, like supporting injections of the additional number of carriers into the system, reducing the operating voltage, and helping to realise the smooth surface [147]. With a dielectric constant value 3.1 @ 10 KHz for the film thickness of 50–200 nm, Shellac offers hysteresis free behaviour with a low density of the impurities or irregularities that would trap charges and cause performance loss [21]. This lack of hysteresis in the OFET makes shellac a desirable material at par with commercial dielectric materials like PVA and PMMA. However, the major drawback of shellac is its brittleness, which can be dealt with sound material engineering using specific plasticizers.

5.3. As an adhesive and cement

Shellac is used as an adhesive for laminated paper, jute boards, Si-chips and solar cells. It is a good plate sealer. Shellac works as a polymer adhesive used as a gasket cement, general cement and optical cement. Shellac can be used as a thermoplastic cement composition from shellac to bind bricks, wood, slabs, ornamental tiles, and glass and pottery metals [148,149] and flexible, waterproof and heat resistant leather cement [150]. Asbestos, *gutta-percha* and *caoutchoue*, types of cement resistant to many chemicals and solvents, were created using shellac. Thermoplastic cement was made using shellac and *gutta-percha*, which were used to unite silk, joint leather, caulking of ships, metals, glass, stone earthenwares, etc. [151].

Many studies were done for adhesive cement composition. Many investigators made such compositions that could combine glass to glass, glass to metal and metal to metal [152,153]. Shellac can be used as heat and water-resistant adhesive, which can tolerate even 130 °C temperature, especially for binding grinding wheels to metallic mounting on rotating shafts [154], synthetic rubber-based cement, which is suitable for gas musk [155] and boiling water resistant cement for fabrics [156]. A composition was made of shellac for fixing steam pipes, receptacles, and water pipes for sealing a joint or crevice to stop leaking and for mounting lenses. Shellac is used as an adhesive for lamination of jute boards [157], paper laminated boards [99], laminated fiberboards [158], manufacture of plywood [99], the rigid composition of sealing corks of bottles [159], sealing pneumatic tires [160], non-inflammable sealing wax for electrical insulation [9,161] and as a sealing wax in candles [162].

5.4. As a coating agent

Due to its eco-friendly and non-toxic nature, the US FDA has labelled food-grade shellac as ‘generally recognized as safe’ (GRAS) [43,124], and European Food Safety Authority also has approved shellac as a food

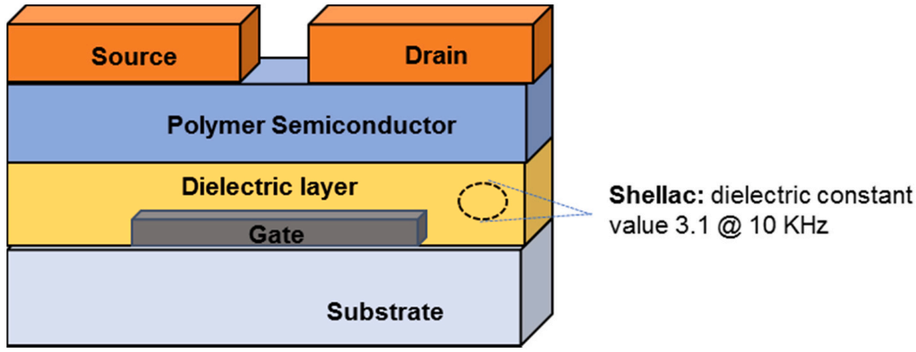

Fig. 8. Constituents and design of OFETs using shellac as a dielectric layer.

additive (E904) [16,163]. Shellac has excellent film-forming and binding properties that, combined with its bio-compatible nature, make it an excellent choice as a coating agent [164]. Coating various fruits and vegetables with water-resistant material has been found effective in extending their post-harvest shelf life. Because of the increasing awareness about natural products and evidence of health issues with synthetic waxes used for coating, shellac or shellac-based coating has been gaining popularity and reported in several studies [165,166].

Chitravathi and coworkers did work on post-harvest shelf-life extension of green chillies in 2014. It was found that if green chillies are coated with shellac, starch, EDTA and sodium alginate, the storage life of fresh green chillies could be increased to 12 days. It was also suggested that shellac mixed with sodium alginate and applied over chillies, kept at 26 ± 2 °C, RH 68 ± 4 % ambient temperature, gave the best results [42]. Shellac was used as a coating material by Musa and coworkers on the internal quality of chicken eggs. Different amounts of shellac solutions were kept on different storage days at 40 °C. No lousy change occurred in the internal quality of eggs [43]. Coating mangosteens and limes with shellac-based formulation improved the gloss, reduced weight loss, and preserved fruits 14 and 41 days longer than the control [167].

A shellac coating was applied to grapefruit for the biocontrol of *Penicillium digitatum*. The coating of shellac supports the population of yeast *Candida oleophila* [50]. On using shellac, the Yeast population remained from 10^4 to 10^5 for four months, due to which the shelf life of grapefruit improved. Shellac has been used to coat apples for a long time, but according to a study, apple pieces coated with shellac can be kept for 30 days at 6 ± 1 °C [40]. The surface coating results in reducing respiration rate, ethylene synthesis rate and electrolyte leakage. Shellac can also be coated on cut slices as it reduces the enzymatic activity of polyphenol oxidase and peroxidase enzymes. Jo and coworkers used carnauba–shellac wax (CSW) containing lemongrass oil for fuji apples' quality and microbial safety [41]. Their study indicated no change in the hardness of coated apples that were stored for five months. Weight loss was 5.25 %, total aerobic bacteria decreased, and yeast and moulds were also not found, so it is suitable for maintaining CSW coating quality for extending shelf life.

Shellac and *aloe vera* gel-based surface coating formulations for tomatoes were developed and evaluated [124]. The coating was found effective in checking respiration, thereby reducing ethylene synthesis and delaying senescence. These coatings could extend the shelf-life of tomatoes by 8–12 days when stored under ambient storage conditions. The effect of shellac, gelatin, and Persian gum on the quality attributes of orange fruit was compared [168]. Coatings successfully improved the quality of Valencia oranges as they decreased weight loss, retaining the firmness and flavour of the fruits. The shellac was the most promising coating agent out of different treatments due to its non-sticky, odourless, fast drying and gloss-imparting properties.

A combined effect of electron beam irradiation and shellac coating on the storage of lime fruit was observed in a study [51]. Here it was reported that if *E*-beam irradiation is done on fruits without coating, the weight loss and respiration rate increase, but if there is a combination of these two, then there will be changes in ΔE values, L*, a*, b*, total chlorophyll content. It decreases acidity and increases ascorbic acid and H_2O_2 content. The effects of shellac and gelatin composite film were studied on bananas [52]. A composite film of 60 % shellac + 40 % gelatin was made for coating the banana, and it was left for 30 days at 25 °C. From the study, it was stated that the coating acts as a physical barrier. The fruit's weight loss, softening, and amount of acid and sugar slowly decreased after coating. Apart from this, there was no change in the post-harvest quality of banana fruit for 30 days or more.

5.4.1. Shellac in electrospinning and electrospray

Electrospinning and electrospray are the electrohydrodynamic processes where polymer solution is released from a thin nozzle under high voltage to form nanofibers or nanodroplets and then solidify. A typical set-up of electrospinning and electrospray devices, including a high-voltage power supply, a syringe pump, a spinneret, sprayer and a conductive collector [169], is shown in Fig. 9. Generally, this is not very easy to perform for natural polymers due to the behaviour of the polymer solutions or melts and the specific conditions required to form solutions and maintain a liquid state. Shellac being easily soluble and stable in anhydrous ethanol solution and low molecular weight gives it an upper hand in making an electrospinning or electrospray solution [170,171]. Due to polymer chain entanglement, Shellac also acts as a filler for nanofibers imparting thicker nanofiber with other polymers like polylactic acid (PLA) [172]. This effect can be reduced using ethanol as sheath fluid, forming thinner shellac nanofibers without compromising their quality.

5.5. As a cosmetic

Shellac is used as a nail polish [173], and it acts as a binder for mascara. Lac bangles are manufactured in many states of India like Rajasthan, Uttar Pradesh, Bihar, Andhra Pradesh and West Bengal. A considerable amount of shellac is used to make bangles. Moradabad and Jaipur are India's areas known for making lac bangles. Gold and silversmiths use shellac for filling hollow jewellery. Shellac is used as an ingredient in hair spray and shampoo formulations. In micro-encapsulated perfumes and lipstick also, shellac is used [123,174–176].

5.6. In printing ink formulations

Shellac is used as food-grade ink [177], lithographic ink, waterproof ink and colored ink. For non-toxic food packaging printing, shellac is utilized as flexographic printing inks. Since the 1960s, shellac has been used in printing ink formulations because of its good wet ability and the ability to retain tinctorial strength. Inks have good storage ability and water resistance [76]. Shellac is also utilized in substrates for adhesion improvement, moisture resistance, glass provision, and various

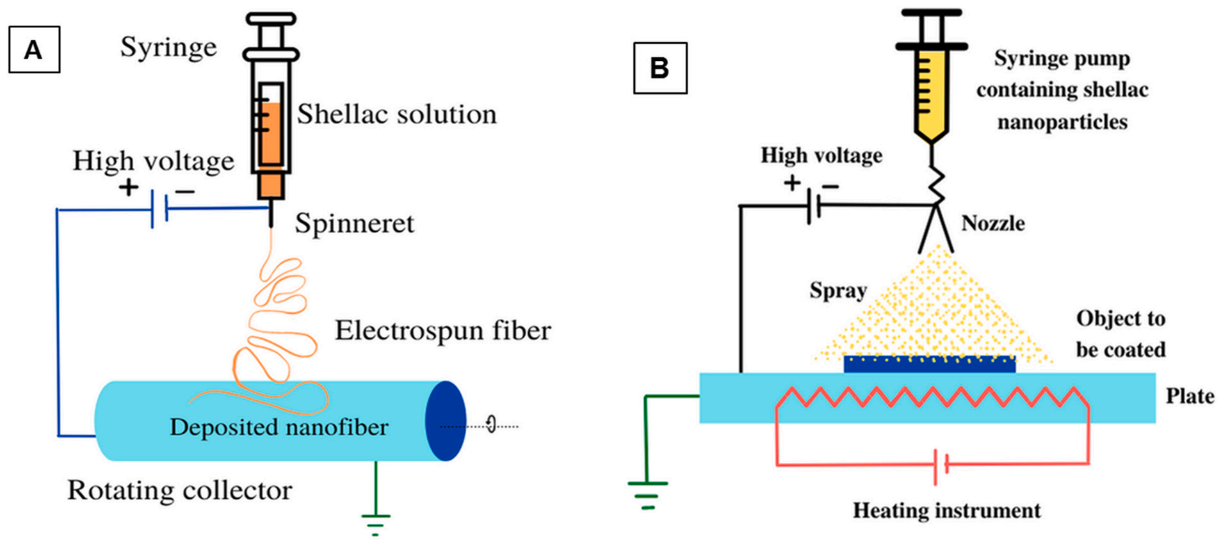

Fig. 9. Application of shellac in (a) electrospinning and (b) electrospray.

flexographic ink formulations [178–183]. Due to the non-toxic nature of shellac, it is used in the formulation of edible ink printing in medicines and other foods [184]. In lamination, shellac acts as water-borne laminating ink [185]. It is also used in stencil spray printing inks and lacquers with the help of shellac [123,183,186].

5.7. In leather finishes

Shellac has been used to finish leather [187,188] for centuries and leather fabric [189]. Different compositions of shellac are used for dying and lacquering, toughening leather. Shellac is used as thermoplastic filler in soles and boots [190] to protect the leather from shrinkage [191], high lustre shoe dressings [192], colored coatings [193] and green bronze finish [194]. Shellac based lacquer helps finish rubber-coated leather [123]. It is also utilized as a liquid leather shoe polishes, leather shoe polishing cream [195], manufacturing of artificial leather [196], in the cleaning composition of shoes, metallic finishing of leather by mixing shellac with graphite, shellac as a stiffener for chrome tanned leather [123].

5.8. Shellac-rubber combinations

Shellac is compounded with rubber because of resin/wax/dye in it. Due to the low molecular weight of the resin, it acts as a plasticizer like filler in rubber. Scott was the first scientist to use shellac as an ingredient in the rubber composition. Mixing shellac in the normal process like raw rubber has the advantage that it does not break during mastication [197]. It vulcanizes much harder when mixing shellac in a small amount with a larger proportion of filler (china clay or carbon black). Shellac was found inert towards the ageing of vulcanized rubber, which is not harmful also. If 25 % shellac is mixed with styrene butadiene rubber (SBR), tensile strength, tear resistance, and hardness improve [123]. Likewise, if natural rubber is mixed with blended shellac or ethylene glycol modified shellac, mooney viscosity, scorch time, modulus, and tear resistance improve [198]. When SBR is compounded with shellac, the tensile strength, tear resistance, hardness, and hydrocarbon solvent resistance become good [123,199]. A later study showed that the compounding of Zn-salt and SBR of shellac improves the mechanical properties of both SBR and shellac. The dielectric properties of natural rubber and SBR improved upon compounding with shellac [123].

5.9. Shellac polymer/resin blends

The polymer is blended for the best end product in the polymer industry. For developing copper wire insulating enamel composition, shellac and polyamide were heated in m-cresol and then dissolved in solvent naphtha. When it was kept at 320 °C for 90 s, the result was satisfactory for copper wire. High thermal (~230 °C) and water-resistant films can be obtained if shellac solutions are mixed with alkyd and polyamide resins [200]. Smooth air-dried and baked (150 °C) films can be obtained when shellac is blended with polyvinyl alcohol. These films have good adhesion and flexibility properties. Many products such as topcoat adhesive (nitrocellulose), wood varnish (amino resins polyurethane), insulating coating (epoxy), coating for textile (PVC+ polyvinyl acetate), adhesive for bonding mica [201], printing ink (naphthol formaldehyde) can be obtained if it is mixed with polymer shellac [123]. Shellac filled synthetic resin fibreglass mats can be used to make tea coasters. Shellac blended with novolac resin [202], epoxidised-novolac resin [203,204], and rosin have modified and improved properties as coating agents for various surfaces. Sheets can be prepared from shellac-based high thermal resistant insulating varnish using layup techniques [205].

5.10. In the pharmaceutical industry

Another fascinating application of shellac can be seen in pharmaceuticals as a popular area of research. Lac and lac derived substances are used in making several pharmaceutical coatings. One of the more recent advancements in this sector is the development of shellac-coated sustained-release pellet formulations [164]. It is used for the microencapsulation of vitamins, and the coating of many medicines as the lac coating on medicines restricts the sudden release of active ingredients into the body. It is also used to make Ayurvedic and Unani medicines [121], such as hiccups, cough, osteitis, osteomyelitis, dropsy and diuretic, anti-obesity, and anti-inflammatory agents. Shellac-alginate based formulation was also found helpful for the encapsulation of peppermint essential oil [206]. Quercetin fortified self-assembly of novel almond gum-shellac nanoparticles revealed improved antioxidant activity [207].

A study was done to develop oil capsulation systems using alginate/shellac as wall material. The semi-spherical, smooth-surfaced beads had an encapsulation efficiency of 98.7 % and total oil content of 38.6 %. Beads release more oil in intestinal digestion than in gastric digestion [208]. The developed system has the potential for making new products in the food industry due to its delivery capacity in oil encapsulation and oil-soluble compounds. Bioactive compounds taken orally have to reach the gastrointestinal tract by crossing the stomach's acidic environment barrier. It is, therefore, necessary to prevent the molecules from degrading in acidic pH in the delivery system and releasing it into the small intestine. The unique property of shellac being insoluble in water at neutral to acidic pH and soluble in alkaline pH makes it an ideal drug coating material intended for colon target release. As depicted in Fig. 10, when a particular drug is coated with shellac, it prevents or restricts the use of an active ingredient in the acidic pH of the stomach and releases the maximum portion of it in the intestinal alkaline environment making it a pH-sensitive smart release material. Patel and coworkers developed pH-responsive colloidal particles of shellac to test the target-specific delivery of silibinin drugs. The drug encapsulated with the shellac particles could sustain the acidic pH environment and release a significant part of it (>90 %) in the alkaline pH, similar to GI tract pH [209].

Fabrication of oat protein shellac beads at neutral *pH* was studied. The structure restricts swelling, which prevents premature riboflavin diffusion and protects 85.5 % survival and 80 % amylase activity of *L. acidophilus*. So, it was suggested that shellac beads are capable of future delivery systems of sensitive bioactive compounds in food and biomedical applications [210]. Cinnamon bark extract containing shellac nanoparticles was synthesized and stabilized with xanthan gum to study the pH-responsive delivery system [211]. The particles were found stable in the acidic stomach environment, and >90 % of the active ingredient (cinnamon polyphenol having antioxidant properties) was released in the alkaline pH, similar to the pH of the intestine. Moisture-protective matrix tablets using shellac coatings were prepared, which were found successful in taste-masking and extended-release [46,125].

Various matrices or formulations developed based on shellac have been reported to exhibit controlled release behaviour of different drugs such as metronidazole [212], monolaurin [213], doxycycline hyclate [214] and theophylline [215]. Also, coating the shellac on drug tablets improved the mechanical properties and efficiency of the drug-coated [111]. An in-situ forming gel containing bleached shellac and other shellac-based gels also showed desirable drug release properties for doxycycline hyclate and other drugs to treat ailments like periodontitis [216–220]. Besides this, custom-made shellac-based nanofibers prepared by the electrospinning process [170,221] also exhibited excellent drug release properties. Phaechamud and coworkers investigated bleached shellac based solvent exchange induced in situ forming gels helpful in injectable formulations as a carrier of different drugs [222–224]. Bleached shellac in solution phase, when comes in contact with some non-compatible or aqueous solvent, converts itself to opaque rigid gel which remains suspended in the resultant matrix. Increasing the concentration of bleached shellac increased the viscosity of the formulation, gel formation and duration of drug release but reduced the injectability [219]. Efforts were made to improve the injectability, gel-forming properties and antimicrobial properties of in-situ forming microparticle formulations by using different oils as the external phase of non-aqueous oil emulsion [220], using solvents like *N*-methyl pyrrolidone [219] and by using different solvents like *N*-methyl pyrrolidone, dimethyl sulfoxide, 2-pyrrolidone and eutectic (1:1 menthol: camphor) [216]. Various solvents have shown different viscosity and injectability for bleached shellac and 2-pyrrolidone emerged as the most suitable solvent for bleached shellac based in-situ gel forming formulations [216]. Shellac has also been found helpful in tissue engineering applications. Jacoby and co-workers fabricated the capillary-like structure of macro inlet and outlet vessels using a shellac blend and observed a thrombosis-free movement through the network imitating the arrangement of true capillary [19].

Shellac has various applications as a film in the pharmaceutical industry due to its low water permeability and controlled release properties. Nevertheless, due to its low stability, insolubility at neutral pH, and need for an organic solvent to get dissolved, the use of other polymeric counterparts like cellulose derivatives and poly-acrylates gained preference [45]. Several efforts were made to improve the stability and properties of shellac films by partial hydrolysis [45], alkali treatments [225], use of plasticizers like jeffamine® [226], gelatin, polyethene glycol and diethyl phthalate [227]. Also, the effect of various plasticizers on film and other shellac properties is discussed in detail by Qussi and Suess [228] and Luangtana-anan and co-workers [229].

An investigation was done for shellac's moisture protection and taste-making potential. It was found that tablets with shellac coating exhibited less water absorption rates. The stability of the drug, acetylsalicylic acid, was also found more in shellac coated tablets. These tablets require a lower coating than common cellulose derivatives with similar effects without changing drug release properties. Coated tablets worked as a matrix for extended-release of the drug, and the annoying flavour of acetaminophen was also suppressed [125]. Multiple layer coatings to

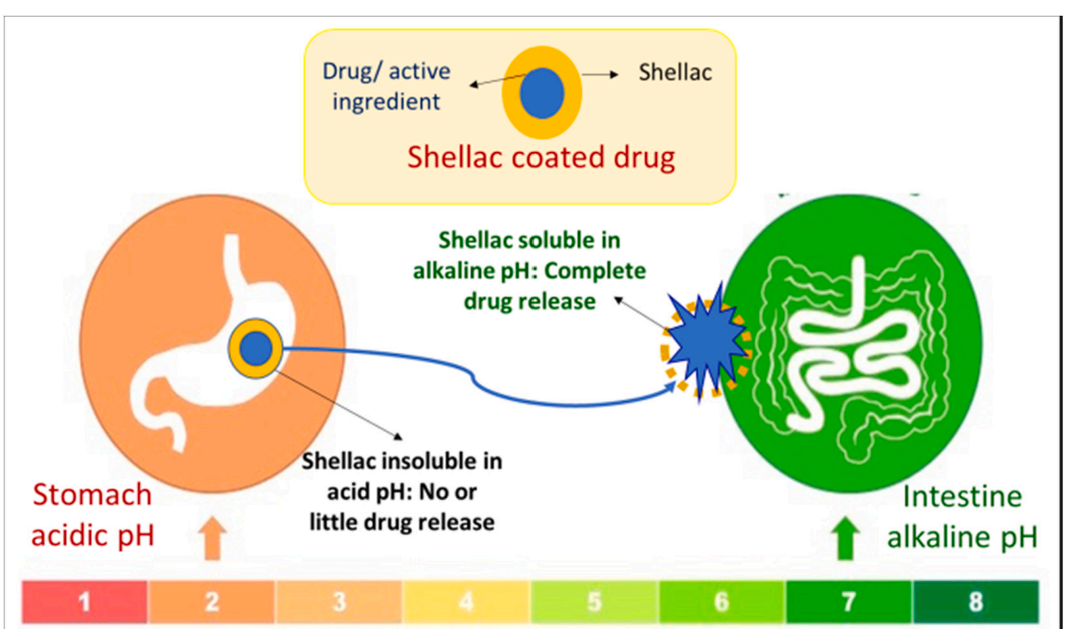

Fig. 10. Mechanism of targeted drug release through shellac coating.

pellets using calcium chloride, citric acid, etc., for the enteric sub-coat and shellac for the outer sub-coat were tried for the controlled release of theophylline [164]. The coatings could prolong the release of the drug in the surrounding media. As different sub-coats have different interactions with shellac, this modifying sub-coat technique can be used to develop custom-made drug delivery systems.

5.11. Other uses

As a low-temperature fuel; in the photographic and engraving industry; dental compositions; for increasing the strength and longevity of shoes; encapsulation of fertilizers and pesticides for their slow release; preservation of fruits and eggs; in preparation of toys, buttons and pottery; in making hats because of moulding ability imparted by lac.

Shellac can be used as a binder for pencils [123]; in cleaning oil-coated aluminium surfaces, soft drink formulations create artificial turbidity, de-icing and anti-icing composition, increasing air permeability in organic fertilizers, injection moulding, and preparing cold enamel [230–235]. It is also used to prevent contamination of microbes from cattle hides to beef; the hides were treated with shellac solution [236]. The results revealed that microbial reductions were up to 3.6 $\log_{10}$ CFU/cm^2 of the total viable count of bacteria, up to 2.5 $\log_{10}$ CFU/cm^2 of Enterobacteriaceae and up to 1.7 $\log_{10}$ CFU/cm^2 of generic *Escherichia coli*. The coating with shellac was even better than the commonly used sanitiser rinse-vacuum hide process.

In another work, 23 % shellac with ethanol solution was used to prevent bacterial transferability in cattle hides, and it was found that the swab-recoveries of general microflora had decreased by 6.6 logs; and of faecal indicators (generic *E. coli* count and *E. coli*) by factors of at least 2.9 and 4.8 logs, respectively [237]. Shellac can be a main component in embalming techniques [238]. It was also recommended that embalming with shellac is less hazardous and financially more viable.

Shellac was used as a sheet moulding compound to manufacture fibreglass reinforced (FRP) sheets. It was found that the mechanical properties of FRP sheets are improved by the use of small amounts of shellac, and the sheets do not deteriorate in sunlight and show resistance to various chemicals. Natural resin shellac has UV ray absorbing properties also; its use makes FRP sheets more eco-friendly and last longer [239]. Long-chain aliphatic alcohols such as triacontanol (30), dotriacontanol (C32), octacosanol (C28), hexacosanol (C28), etc., are established plant growth regulators. Triacontanol present in the lac wax was isolated, purified and evaluated for the plant growth-promoting activities [240]. According to the study, lac wax derived triacontanol effectively promoted plants' growth, yield, and photosynthesis. A method of the microfluidic system was invented using shellac. It creates a biodegradable end product using renewable materials through energy-efficient fabrication methods. Fabrication of microfluidic materials is done by hot embossing of shellac as shellac maintains the processing temperature and energy [241].

A work on enteric rice protein-shellac composite coating was done. It was reported that coated probiotics pellets are more viable for *L. salivarius*, which protects against thermal treatment and simulated GI digestion. So, it is suitable for fortified product preparation of solid probiotics. The composite coating is also a better option from a preservation point of view [242]. Formulation of shellac on citrus fruits was done to reduce the coliform bacteria [243]. It was suggested that if shellac coating is done after harvesting citrus fruits, the population of coliform bacteria like *Enterobacter aerogenes* and *Escherichia coli* becomes 10^5 CFU/cm^2 to $<2.5 \times 10^1$in 2 weeks.

Patel and coworkers developed a thermo-reversible, soft gel formulation using shellac, comprising liquid oil dispersed into it [244]. By altering the concentration of shellac in the oleogel system, the range of gel strength, texture, and thermal behaviour was achieved, which made oleogel systems with adjustable properties. The stable water-oil colloidal system has the potential to be used for diverse applications. In continuation to the previous work, different applications of the shellac-oleogels in food items were explored [245]. The food applications included water-in-oil spreadable emulsion, an alternative to the oil binding agents in the chocolate paste mixture, and a shortening alternative to prepare cakes. The emulsifier free emulsions (60 wt% water) were prepared and stable for four months. Shellac based fluoride varnish (shellac F) was developed by Hoang-Dao and coworkers and tested for cytotoxicity and efficiency in reducing dentin permeability [29]. Compared to commercially available fluoride varnishes, shellac F showed a substantial reduction in dentin permeability (60 to 76 %). Also having good cellular compatibility, shellac F has the potential to be used commercially as a desensitizing agent.

The various applications of the shellac are summarized in Table 3.

6. Modern applications and future potential of shellac

The journey of shellac research witnessed the various industrial and technological revolutions. From the beginning of the 20th century to the first quarter of the 21st century, there has been a paradigm shift in the scope and application of shellac (viz. adhesive, colorant to forerunner of green electronics). Shellac offers enormous potential to the following modern technological innovations as a natural and environmentally friendly substitute to its existing technology:

6.1. Shellac for the green electronics

Shellac is a natural and biocompatible material with noteworthy insulation and dielectric properties that make it a suitable candidate for its application in electronics [251]. Switching the synthetic substrate material and dielectric layer used in electronics to the naturally occurring shellac has several advantages: low cost, low toxicity, and low environmental impact. Irimia-Vladu et al. have used shellac to devise biocompatible organic field-effect transistors (OFETs). The shellac OFETs perform well in electrochemical tests, making them at par with other dielectric materials of natural and synthetic origin [21]. Aeby and coworkers [252] designed a disposable graphite-based supercapacitor using shellac as organic-green ink for current collector printing as a crucial capacitor component. The shellac acts as a dielectric layer and is used as a matrix for electrically conductive inks. [24] formulated a carbon derived conductive ink in shellac for printing disposable electronics. Shellac acts as a binder for carbon particles in the conductive printable ink, showing properties like low sheet resistance, high mechanical flexibility, stability and compatibility with 2D/3D manufacturing techniques.

6.2. Shellac for nanotechnology

Nanotechnology is commonly known as the study and application of tiny molecules usually <100 nm in size. Shellac is a long chain of polymers of hydroxy aliphatic acid and sesquiterpenoid acid rarely considered for nanotechnology-based research and applications. However, the research works in the pharmaceutical industry and material science open this new horizon for shellac. According to Panda et al., 2018, graphene-based composites exhibit biocidal activities, but it is shown that superior antimicrobial properties of natural shellac-derived graphene oxide coatings are obtained on metallic films, such as Zn, Ni, Sn and steel [246]. The application of shellac with Cu nanoparticles to provide a significant antimicrobial coating on the face mask and shellac functionalized with nanoparticles which enable it for various drug delivery processes, is a remarkable work [253]. Shellac based nano-delivery systems have been extensively studied and developed [18]. Shellac nanoparticles encapsulated on natural food and drinks colorants provided a safe microenvironment for the colorants enhancing their shelf life. The shellac nanostructure with entrapped colorant molecules was stable on a wide pH range and had improved solubility. This could be used in applications related to the food and brewing industry to deliver and release natural colorants in drinks. Wang and coworkers

Table 3
Diverse applications of shellac in a nutshell.

Particular area	Details of shellac applications	References
Pharmaceutical application	Sustained release of vitamins and dietary supplements	[164]
	Tablets coating for the moisture protection and taste-making	[125]
	Shellac-xanthan nanoparticles for drug delivery	[211]
	Oat protein shellac beads	[210]
	pH-responsive colloidal particle	[209]
	Oil capsulated shellac beads for controlled release	[208]
	Enteric rice protein-shellac composite coating	[210]
	Shellac as a dental desensitizing agent	[29]
Shellac as a coating agent	Shellac and gelatin coatings on banana	[52]
	Electron beam irradiation and shellac coating on lime fruit	[51]
	Carnauba – shellac wax containing lemongrass oil coating on Fiji apples	[41]
	Shellac coating on apple slices	[40]
	Shellac coating to grapefruit	[50]
	Shellac coating on eggs	[43]
	Shellac based coating on green chillies	[42]
	Shellac coating on citrus fruits	[243]
Shellac in leather finishes, shellac-rubber combinations and shellac polymer/resin blends	Shellac and alkyd/polyamide resins based on insulating varnish	[200]
	Shellac based rubber composition	[197]
	Shellac with styrene butadiene rubber	[123]
	Natural rubber with blended shellac or modified shellac	[123,199]
	High lustre shoe dressings	[192]
	Colored coatings	[193]
	Green bronze finish	[194]
	In the finishing of rubber-coated leather as a stiffener	[123]
	Thermoplastic filler for leather in the soles and boots	[190]
	Shellac to protect the leather from shrinkage	[191]
Printing ink formulations	Shellac in ink formulations for adhesion improvement, moisture resistance, gloss provision, good storage ability and various flexographic ink	[178–183]
Cosmetic	Shellac in the formulation of hair spray and shampoo	[123]
Shellac in adhesives and cement	Shellac based Thermoplastic cement composition	[148,149]
	Shellac based leather cement	[150]
	Lac based adhesives for different applications	[9,99,152,158,160]
	Shellac based water-resistant adhesives for paper	[156]
Shellac in varnish, lacquer, polishes and electrical industry	Shellac based insulating varnishes	[132]
	Modified shellac with improved dielectric strength	[134]
	Dimethyl phthalate treated shellac varnish	[135]
	Baking type shellac varnish	[136]
	Shellac based air drying type brushable and sprayable varnish	[99,100]
	Heat and solvent resistance French varnish	[102,103]
	Melfolac: heat and waterproof shellac varnish for wood	[104]
	Shellac varnish for protection of dental pulp	[120]
Shellac in green electronics	shellac as biocompatible organic field-effect transistors	[21]
Shellac in nanotechnology	Graphene-based composites for biocidal activities	[246]
Shellac in sensor applications	Shellac-based transistors in gas sensing to measure and identify the concentration of gases	[247]
Shellac in Stealth technology	Suitable microwave absorbing material for radar	[248]
Shellac in 3D printing	Shellac with copper nano-particles for hydrophobic surface coating	[35]
	Shellac for the tooth implant techniques	[249]
Other applications	Production of reduced graphene oxide	[250]
	Shellac in the micro fluidic system	[241]
	Shellac wax components as plant growth regulators	[240]
	Shellac in fibreglass reinforced sheets	[239]
	Shellac treatment to cattle hides	[236,237]
	Shellac as a binder for pencils	[123]
	Shellac based oil/water gel for food applications	[245]
	Shellac in soft drink formulations	[233]

fabricated a colon-specific drug-carrier system using medicated shellac nanofibers [254] using coaxial electrospinning. These nanofibers had pH-specific dissolution, with minimal release at pH 2.0 and gradual release at a neutral pH. Ma et al. studied and improved shellac mediated nanoscale gastric-site drug delivery systems [255]. They developed shellac-sodium carrier systems with high-efficiency encapsulation and enhanced drug release rate at target sites.

6.3. *Shellac for sensor applications*

Shellac-based transistors are used in gas sensing to measure and identify the concentration of gases present in different products. However, active functional groups (hydroxyl and carboxyl) in their structure make it a potential candidate for sensing materials. These gas sensing techniques help us identify toxic gases present in the atmosphere due to various industrial processes and toxic gases produced from contaminated food that affects human health [247]. The material is amphiphilic (Fig. 6), which is also suitable for its application where the orientation of molecules plays a significant role in sensing, as the taste sensing mechanism. Monitoring and maintaining the quality and safety of food in transport and storage from producer to consumer are the most critical concerns in the food industry. Shellac is non-toxic and has edible properties, adhesive binding properties, and low permeability to water vapors and various gases. It has been used as a coating material in the food and pharmaceutical industry to increase the product's shelf life to ensure controlled drug release. Researchers have studied the effect of shellac coating on eggs [256]. Shellac-based coatings may act as a colorimetric sensor, i.e. change in the color can help us identify the contaminated product and degraded food products, representative images of which are shown in Fig. 11.

Henrique et al. in 2021 [145] developed a disposable shellac-graphite electrochemical sensor for sulfamethoxazole detection. Sulfamethoxazole is a common metabolic residue in the food web. The sensor was developed using a conductive ink formulated from shellac on a waterproof paper substrate with gelatin. A relative humidity detection sensor with high recovery analysis for water and milk samples based on shellac was developed [145]. This sensor was designed on sub-micrometer-sized carbon inter-digitated electrodes. This thin-film sensor had high sensitivity to humidity from different gases, with an enhanced response rate compared to generic gas sensors.

6.4. Shellac for Stealth technology

The absorbing efficiency of radar is highly dependent on the composition and structure of the coating. Tremendous efforts have been devoted to engineering the composition of coatings. Microwave absorbing materials possessing exceptional performance for absorbing electromagnetic waves have been applied in civil and military fields and play an essential role in camouflage technology. The strength of the material is determined by its dielectric properties- complex permittivity, AC or DC electrical conductivities, impedance and tan loss, etc. the materials must have a balanced combination of the electrical conductivities, electrical permittivity, and magnetic permeability as well as suitable physical structure and geometry. For achieving effective EM wave absorption, the material must obtain specific impedance characteristics through effective complementarity between dielectric and magnetic losses. Recent trends of EM microwave absorption materials mainly comprise magnetic loss, dielectric loss (especially polarization, such as electron polarization and interface polarization), and other mechanisms to achieve microwave absorption. The fabrication of microwave absorption materials is mainly focused on magnetic materials (magnetic metals, alloys, and oxide), carbon-based materials (CNTs, graphene, carbon fibre), composite materials (magnetic carbon composite), and other nanomaterials (MXene, sulfide, nitride, carbide) with unique structures. Bio-polymers with efficient coating properties are also becoming a choice for this application. Polymers possess a unique shielding mechanism of reflection plus absorption rather than dominated reflection for metals and carbons. Shellac has been a promising material having high dielectric and excellent coating properties. The decrease in dielectric loss with an increase in frequency also enables it as a suitable microwave absorbing material [248].

The dielectric loss in shellac (grade 'Blonde') is lowest in the 8 mm band, and for this grade, measurements of loss have also been carried out over a wide band of radiofrequency [257]. The ability to regulate their electrical conductivity by controlling oxidation state, doping level, morphology and chemical structure makes them a powerful candidate for various techno-commercial applications [258].

Table 4 shows the list of significant patents filed in the last one and half decades with potential applications in the food industry, coating – edible and non-edible, nanotechnology and sensor development. Recent trends for shellac in several patents also promise its future market potential in the major sectors like food processing, biomedical and nanotechnology.

6.5. Shellac in 3D printing

One of the novel applications of shellac was identified in the 1990s when shellac began to be used in dentistry, for making dentures, base plates etc. This paves a new avenue for shellac, which is different from its traditional injection moulding application in product designing. Recent advances in 3D printing technology (additive manufacturing) also hold tremendous research possibilities in shellac as tunable material for prototype designing and other artefacts [282]. With the evolution in material research, shellac composites attracted researchers because of their novel and environment-friendly attributes like natural origin, low melting point, thermo-setting property, modulation of the brittle nature, low cost, and antimicrobial property. 3-D printing technology provides a great help in the biomedical field. Recently, the possibility of using shellac filament in fused deposition modeling 3D printing was investigated by Chansatidkosol and coworkers [283]. The hot melt extruded shellac filament exhibited suitability for use in 3D printing. Destie Provenzano and coworkers in 2020 have designed a 3D printed reusable N95 respirator where shellac can be used as sealant [284]. A conductive ink prepared using carbon particles suspended in a shellac solution was developed recently to be used for screen-printing, robocasting and other such industrial applications [285]. Aeby and team in 2021 developed shellac based graphite flakes and carbon black particles containing ink to be used in disposable paper supercapacitors [286]. The team had successfully 3D printed an article using this functional ink made up from renewable and non-toxic ingredients. The composite structure of shellac with copper nano-particles proved to be a hydrophobic surface coating helpful in imparting antimicrobial properties [35] on the surgical non-

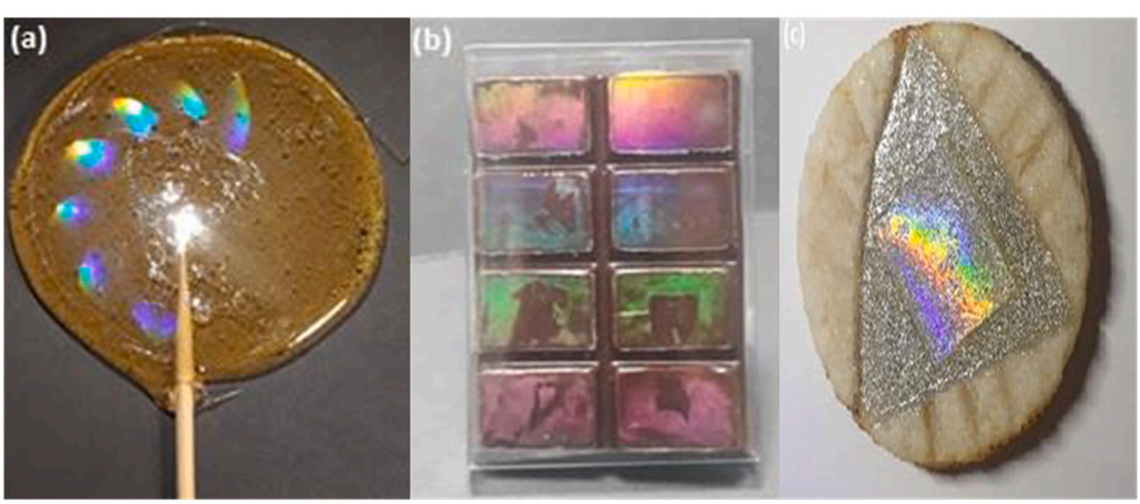

Fig. 11. (a) Shellac hologram on the surface of caramel; (b) Shellac hologram on the surface of chocolate; (c) Shellac hologram on the surface of marzipan 14.

Table 4
Recent patents on the use of shellac in different applications.

Sl. no.	Patent title	Inventors	Year
1	Food grade coating for edible moisture-sensitive particulates [259]	Xiagdong Gan and Michael Mcnelly	2022
2	High-adhesion-strength shellac and preparation method thereof [260]	Zheng Yaochen, Xu Hui, Gao Xuan, Qiao Chenghui, Wang Song Qi, Zhang Wenjie	2021
3	Shellac microcapsule formulations and compositions for topical intestinal delivery of vitamin b3 [261]	Karin Schwarz	2021
4	Oral compound medicinal composition for releasing medicine in colon and preparation method thereof [262]	Liu Zhepeng, Zhai Ruidong, Liu Yicheng, Chen Ruiqi, Wang Jing, Chen Haini and Liu Qifang	2021
5	System and method for manufacturing shellac floss [263]	Sherif Shawki Zaki Hindi	2021
6	Food-contactable super-hydrophobic coating [264]	Tang Yali and Liu Lingxue	2021
7	Cannabis delivery with protective glaze coating [265]	Stephen A. Santos, William E. Barrie and Karen M. Murphy	2020
8	Biocompatible shellac nanoparticles and dispersions thereof [266]	Chén Dōng, Kǒnglínlín, Sūnzéyǒng and Wáng Xíngzhèng	2020
9	Chocolate confectionery preparation method and chocolate confectionery prepared thereby [267]	Ik Gil Cho	2019
10	Shellac and paclitaxel coated catheter balloons [268]	Michael Orlowsk	2019
11	A kind of sensor film for detecting low molecular weight alcohols gas and preparation method thereof and sensor [269]	Lu Shengguo, Wang Shicai and Liang Junwei	2019
12	Metal cans coated with shellac-containing coatings [270]	Amanda Ghantous, Christopher Most and Robert McVay	2019
13	Shellac for increasing heat resistance of varnish, and modification method thereof [271]	Yunnan Chu Shanyuan	2016
14	A process for synthesizng reduced graphene oxide on a substrate from seedlac [272]	K.C. Shyam, K.B. Manish, K.R. Thapan, D. Sumiteshi, K.S. Ranjan, N.S. Yashabanta, K.P. Acht, C. S. Vikas	2016
15	Solvent free shellac coating composition [273]	Margaret Mc Wheeny	2016
16	Cementitious system comprising accelerator particles coated with crosslinked shellac [274]	Wolfgang Seidl	2016
17	Graphene conductive ink and preparation method thereof [275]	Wu Weiping and Shi Honghua	2015
18	Shellac based skin care lotion [174]	William E. Barrie	2015
19	Shellac as taste improver for food and drink [276]	Daisuke Mori, Wen Kashima and Yutaka Kashima	2015
20	Field effect tube gas sensor based on shellac encapsulation/ regulation and preparation method thereof [277]	Yu Junsheng, Han Shijiao, Wang Xu, Zheng Ding	2015
21	Shellac modified nano-magnetic adsorbent, preparing method and application thereof [278]	Chen Long, Gong Jilai, Zeng Guangming, Deng Jiu and Long Fei	2012
22	Shellac enteric coatings [279]	Charles A. Signorino, Terry L. Smith and Stephen Levine	2011
23	Stable shellac Enteric Coating Formulation for Nutraceutical and Pharmaceutical Dosage Forms [280]	Thomas Durig and Yuda Zong	2011
24	Sprayable hand cleaner made of edible shellac and micellular surfactants [281]	Michelle Diaz	2010
25	Food grade ink jet inks for printing on edible substrates [177]	Robert A. Baydo Michael Bogomolny Constance L. Lee	2007

woven respirator and other similar items and helps in reusing the same product multiple times (up to 5 cycles) [287]. The use of shellac resin for additive manufacture may be helpful in general prototyping and biomedical-based prototyping for the tooth implant techniques and surface coating of the material on the body implant to impart better biocompatibility [249].

7. Conclusion

The review covers a range of information in one place, related to the beautiful natural resin, shellac, highlighting things like its production, export potential, different forms, properties, and traditional and modern applications. Being natural, non-toxic, eco-friendly, tasteless, odourless and having many exciting properties for industrial use, shellac has a tremendous potential to be used in several industries. The properties of this resin, such as film-forming ability, solubility in spirit-based or alkaline solvent but resistance to water, chemical transformation at higher temperature to become an entirely different and stable material, etc., make it a unique natural material to be further explored in new domains. Besides its existing applications, it has a bright future in developing many more new products and greener technologies, creating a better world to live in.

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Data availability statement

The data that support the review are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

NT: Conceptualization, Writing - original draft & editing; SK: Writing & editing; UK: Writing - original draft; PS: Writing; RKY: Writing; NP: Review & editing; KKS: Supervision and editing.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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