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REVIEW PAPER

Lemongrass (*Cymbopogon*): a review on its structure, properties, applications and recent developments

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Abstract This review addresses the structure, properties, applications and future scope of lemongrass, which constitutes an abundant source of plant material around the world. As a source of cellulose, it has been successfully used for the adsorption of metal ions and dyes and for manufacturing paper and pulp. Recently, it has shown promise in the production of composites and bio energy, as well as obtaining silica and other metal oxides. However, previous research studies have mostly concentrated on utilizing the biological activities of the constituents in therapeutic uses, food preservation, cosmetics and agriculture. Therefore, this review covers literature on all areas of current studies on lemongrass and identifies its multidimensional potential. Furthermore, this review describes the intended application of lemongrass as a source of cellulosic matter, more specifically in the materials science field.

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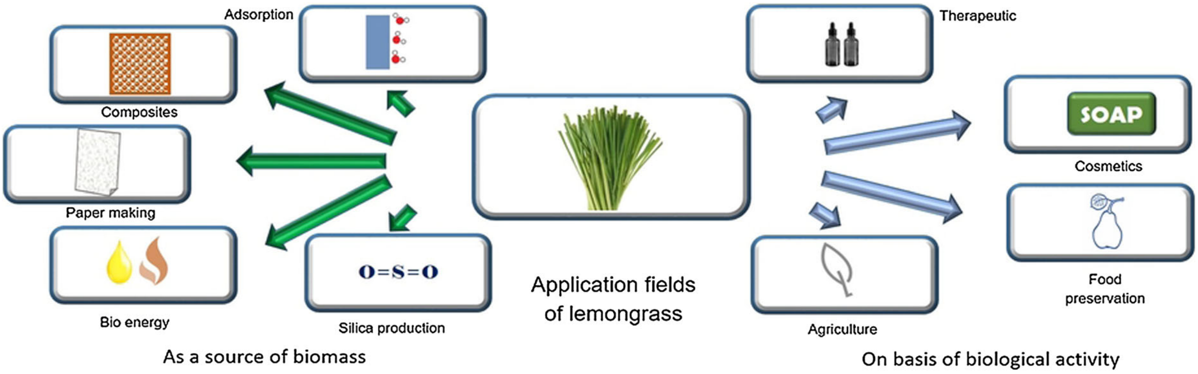
Graphical abstract



Keywords *Cymbopogon* · Biomass · Lignocellulose · Cellulose · Hemicellulose · Material

Introduction

Lemongrass is a popular plant and an abundant source of lignocellulose material composed of around 39.5% cellulose, 22.6% hemicellulose and 28.5% lignin (Bekele et al. 2017). The *Cymbopogon* genus widely grows in tropical and subtropical lands of the Indian subcontinent, South America, North America, Africa, Australia and Europe (Skaria et al. 2006). This grass is so named for its distinctive citrus aroma of the green leaves when they are crushed (Ravinder et al. 2010). It is also known as "Squinant" or "Citronella" in English, as well as other informal names around the world (Kumar et al. 2009; Ravinder et al. 2010; Adhikari et al. 2013; Ranade and Thiagarajan 2015).

Lemongrass is cultivated over an area of 16,000 ha throughout the world which generates around 1000 t of essential oil per year. The grounds on which it is cultivated are mostly infertile and wastelands (Joy et al. 2006). In addition, cultivation of this grass offers a profitable source of earning for low income cultivators, as each hectare of land produces a net profit of approximately 300 USD per annum to the growers (Singh and Jha 2008).

The plant generally grows up to 1.8 m high and 1.2 m in width. It has a small rhizome, and the leaves appear from the soil directly without any stem. The leaves are 1.3–2.5 cm in width and around 1 m in length (Shah et al. 2011). The *Cymbopogon* genus is comprised of more than 55 species in different countries all over the world possessing various material and chemical properties (Abdulazeez et al. 2016). However, *Cymbopogon flexuosus* and *Cymbopogon citratus* (also known as West Indian and East Indian lemongrass, respectively) represent the two major species vastly cultivated in different regions of the world for the high citral content (70–80%) in their essential oils (Robbins 1983).

The pleasant lemon fragrance of this grass has long been used in perfumery and related cosmetics, as well as food industries (Ranade and Thiagarajan 2015). Initially, lemongrass was used to flavour foods in Thai and Vietnamese cooking. It has a beneficial use in African and South American regions for flavouring tea. It is also popular in alcoholic and non-alcoholic drinks (Abdulazeez et al. 2016). Additionally, it has conventional uses in Ayurveda as a tranquilizer, diuretic, antipyretic and anti-inflammatory medicine (Carlini et al. 1986; Negrelle and Gomes 2007). There are numerous examples of the application of lemongrass for health remedies by different ethnic groups (Ravinder et al. 2010). For instance, tea made from lemon grass leaves is predominantly used as an antispasmodic, analgesic, antipyretic, sedative, diuretic and anti-inflammatory compound in Brazil (Leite et al. 1986; Souza et al. 1986). It is used for lowering blood pressure and treating catarrh and rheumatism in Cuba, as well as used to cure the sore throat and empacho in Argentina (Carbajal et al. 1989; Filipoy 1994). In addition, a number of biological properties of lemongrass are reported over the years, including but not limited to antibacterial, antifungal, antiprotozoal, anti-inflammatory, antioxidant, antitussive, antiseptic, anti-carcinogenic, cardio-protective and anti-rheumatic activities (Ekpenyong et al. 2015).

Such a broad variety of activities of lemongrass has made it a preferred choice for research and applications, especially in recent years. Figure 1 represents the number of titles published during 2000–2017 on lemongrass in the Web of Science and Scopus database, which reflects a significant increase in lemongrass research in recent years.

However, the applications of lemongrass are mostly reported on the basis of its biological and correlated activities with its developments in medical science, food science, and cosmetics, as well as agriculture. Reports are also present on the successful use of lemongrass in materials science as a raw matter in pulp and paper production (Kamoga et al. 2015), producing energy (Alfa et al. 2014), as an adsorbent (Hassan 2016), a basic constituent of composites (Bekele et al. 2017) and in the production of silica (Firdaus et al. 2015). Figure 2 describes both aspects of research applications in current years with lemongrass.

The purpose of this review is to comprehensively evaluate the properties and applications of lemongrass and to explore the future applications. Although there are several reviews available on lemongrass reporting only its phytochemical and medicinal prospective, this review aims to cover all of the current application fields of lemongrass together with its structure and properties.

Composition, properties and activities of lemongrass

Lemongrass has three basic components: cellulose, hemicellulose and lignin (Kaur and Dutt 2013; Bekele

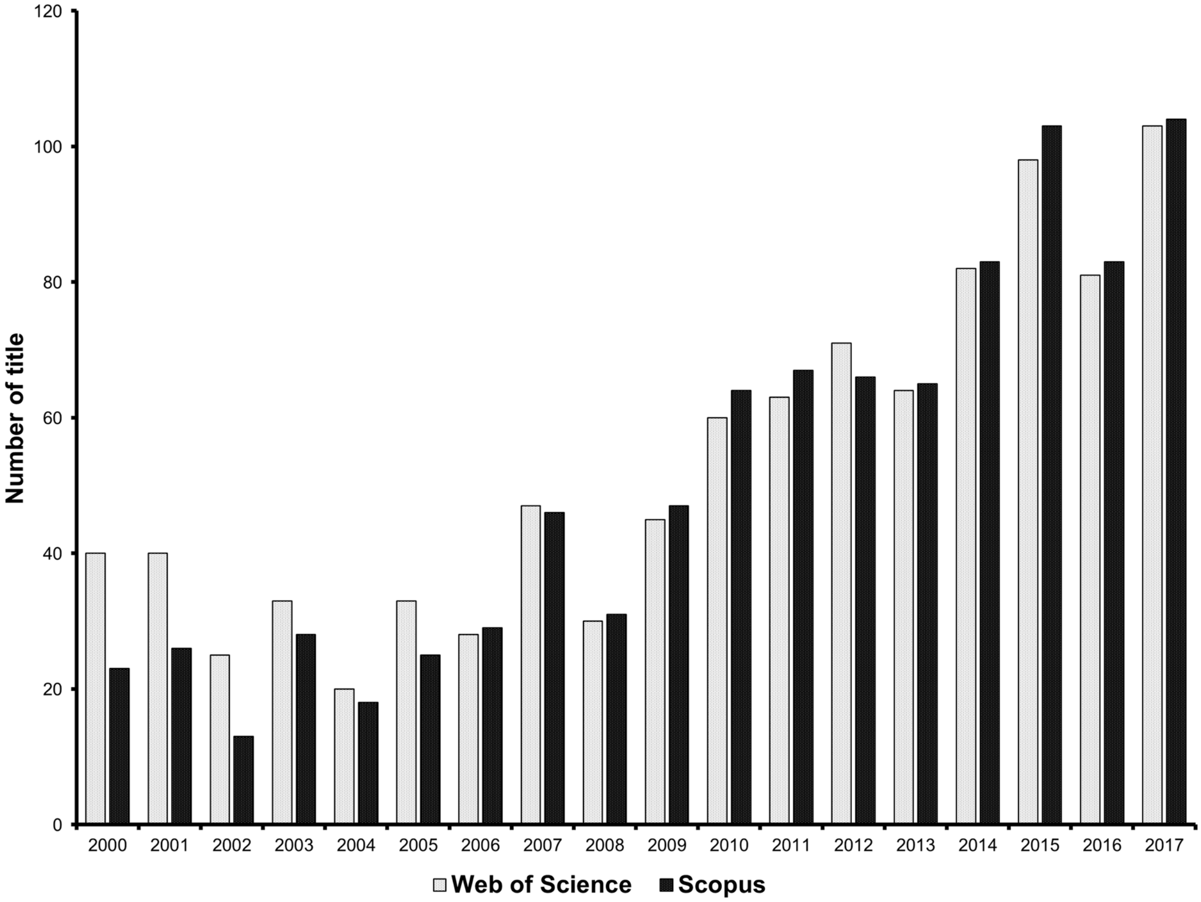


Fig. 1 Number of titles published in Web of Science and Scopus database containing the word “lemongrass” or “lemon grass” or “Cymbopogon” from 2000 to 2017

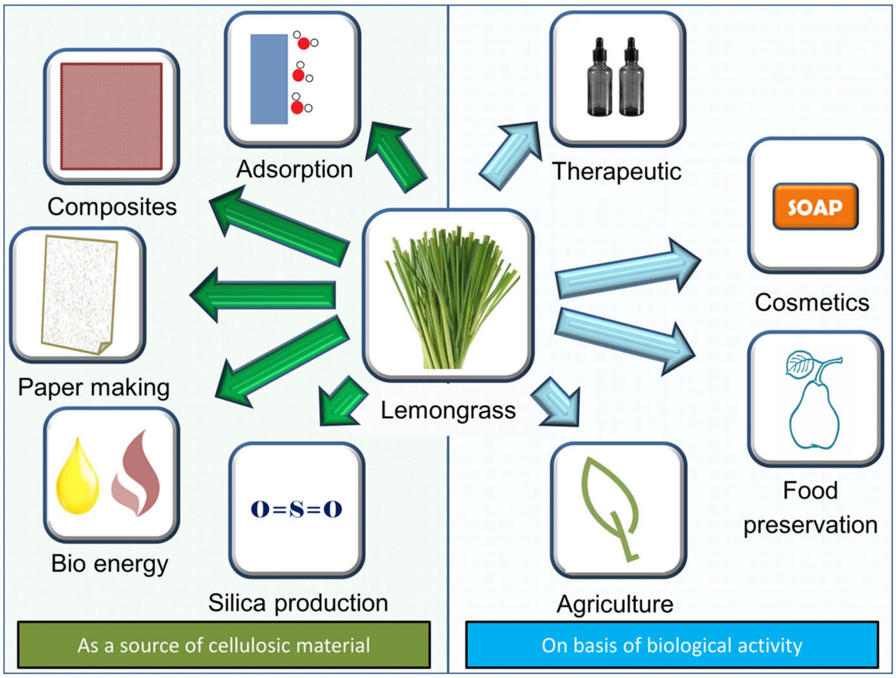


Fig. 2 Applications of lemongrass in different fields

et al. 2017). The chemical constituents of the lemongrass plant are listed in Table 1. Structurally, lemongrass is the hydrocarbon mainly composed of carbon and oxygen. The elemental composition (without ash) of lemongrass is also tabulated in Table 1.

Cellulose is a three-dimensional linear molecule structure, which includes both crystalline and amorphous regions, whereas hemicellulose consists of a mainly amorphous region with several crystalline regions. Another basic difference between cellulose and hemicellulose is the degree of polymerization, which can be 100–10,000 for cellulose and less than 200 for hemicellulose (Yang 2008). Lignin is an amorphous heterogeneous three-dimensional nonlinear polymer which binds cellulosic components together (Bajpai 2016). Cellulose is made up of 1,4 β-glucopyranose units, hemicellulose comprises xylose, galactose, arabinose and mannose sub units and lignin consists mainly guaiacyl, syringyl and *p*-hydroxyphenyl units (Pierson et al. 2013). The structures of cellulose, hemicellulose and lignin are shown in Fig. 3.

Furthermore, there is a variety of oil content found in lemongrass depending upon the genetics, area of growth, culture and agronomic treatment. Generally, essential oil (EO) is collected around 1–2% of the total dry weight (Carlson et al. 2001). However, the method of drying can influence the composition. Oven drying of leaves can produce a greater amount of EO than sun-drying or shade-drying methods, although the oil collected from shade drying has a higher citral content on which the quality of oil is judged (Hanaa et al. 2012).

Table 1 The chemical constituents and elemental composition of lemongrass (Bekele et al. 2017; Madhu et al. 2017)

Chemical constituents	Amount %	Elements	Amount % (excluding ash)
Cellulose	39.5	Carbon	39.34
Hemicellulose	22.6	Oxygen	53.30
Lignin	28.5	Hydrogen	5.81
Ash	1.5	Nitrogen	1.54
Moisture	6.8	Sulphur	0.01

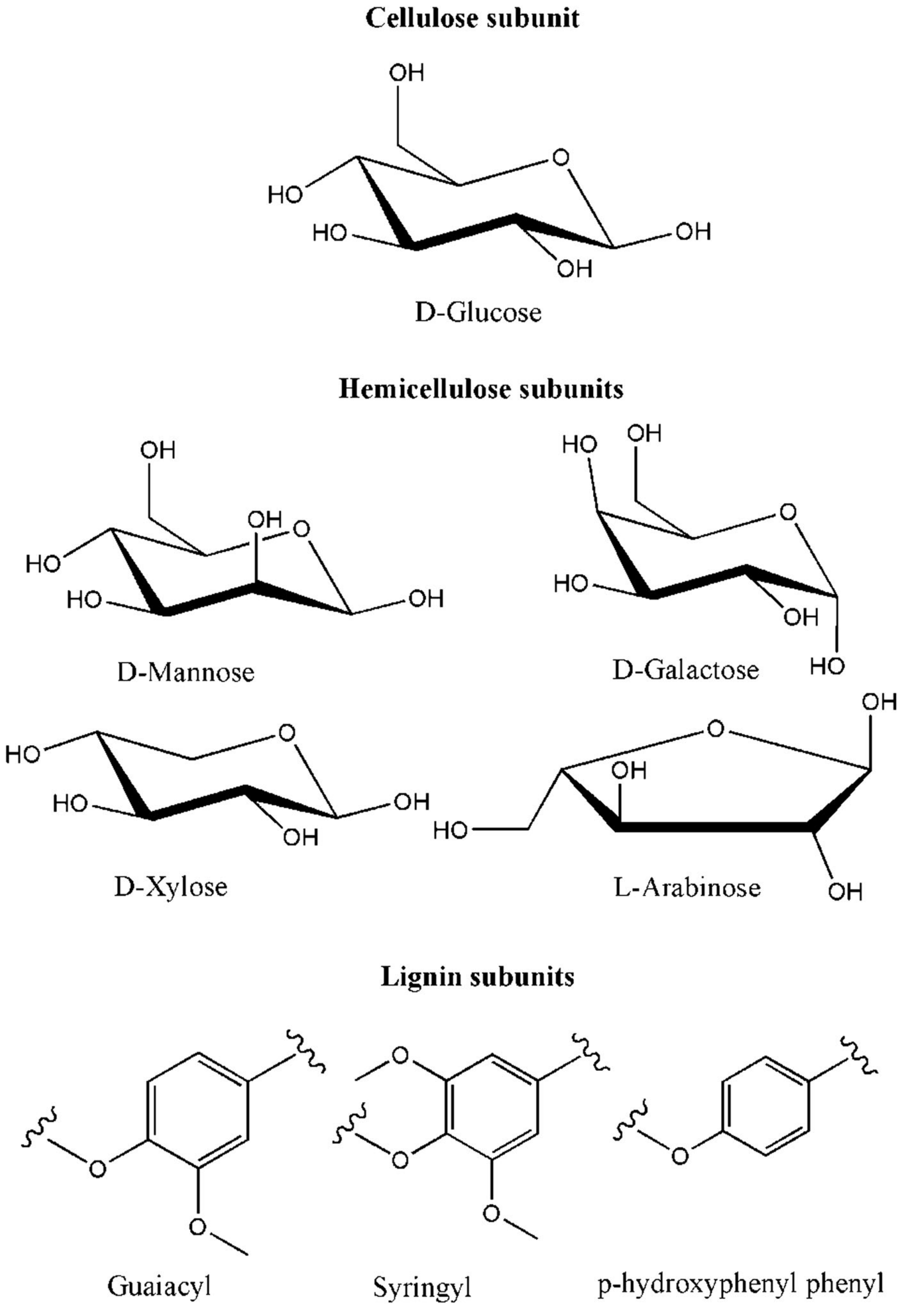


Fig. 3 Structures of major subunits in lignocellulose

Citral is comprised of mainly two stereo-isomeric mono-terpene aldehydes: geranial and neral, *trans*-citral and *cis*-citral (Sarer et al. 1983; Rauber et al. 2005). In general, lemongrass oil contains greater than 45% of citral, but the amount can vary widely among species. The East Indian lemongrass (*C. citratus*) commonly possesses around 30–94% of citral (Negrelle and Gomes 2007; Moore-Neibel et al. 2012). Different hydrocarbons such as terpenes, alcohols, ketones and esters, are also reportedly found in the composition of EO (Abegaz et al. 1983; Evans 2009). The phytochemical composition of *C. citratus* also includes tannins, saponins, anthraquinones, phenols, flavonoids and alkaloids. In addition, myrcene, geraniol, borneol, citronellol, limonene, α-terpineol, elemicin, nerol, catechol, luteolin, apigenin, quercetin, kaempferol, glycosides, chlorogenic acid, caffeic acid, geranyl acetate as well as methylheptenone, isovaleric aldehyde, fumesol, L-linalool, furfurol, isopulegol, *n*-decyclic aldehyde, *p*-coumaric acid, terpinene are also evident in trace amount in several studies (Faruq 1994; Miean and Mohamed 2001; Negrelle and Gomes 2007; Akhila 2010). There are also reports on the presence of isoscoparin, swertiajaponin, orientin and other phytochemicals in lemongrass (Cheel et al. 2005; Bharti et al. 2013b). The amount of major constituents of lemongrass EO found in studies of Saleem et al. are represented in Fig. 4, which shows a greater presence of *trans*-citral (geranial) and *cis*-citral (neral) along with more reduced amounts of nerol, geraniol, citronellol, terpinolene, geranyl acetate, myrcene, α-terpineol and other components (Saleem et al. 2003a, b). The chemical structures of the key constituents of lemongrass EO are shown in Fig. 5. Different minerals are also present including potassium (54.02%), calcium (25.87%), silica (9.02%), phosphorus (1.57%) (Firdaus et al. 2015). It also possesses vitamins A, C, and E and folate, niacin, pyridoxine, riboflavin, as well as protein, carbohydrates and fat (Aftab et al. 2011).

Scientific studies have revealed that lemongrass is effective as an antifungal, antibacterial and antiprotozoal agent (Kishore et al. 1993; Mishra and Dubey 1994; Wannissorn et al. 1996; Vinitketkumnuen and Lertprasertsuk 1997; Tchoumbougnang et al. 2005; Pedroso et al. 2007; Bassolé et al. 2011; Revathi et al. 2012; Azeredo and Soares 2013; Tadtong et al. 2014; Gilling et al. 2014; Karbach et al. 2015; Trindade et al. 2015) which have opened a diverse area of application of this grass. The anti-nociceptive and anti-inflammatory characteristics of lemongrass also confirmed by several studies (Viana et al. 2000; Wannissorn et al. 2005; Boukhatem et al. 2014).

Some studies were conducted to find out the specific biological activities of different constituents in the EO of lemongrass. It was reported that citral and geraniol are responsible for fungicidal behavior, while the presence of myrcene enhances that antifungal activity further (Onawunmi et al. 1984; Moleyar and Narasimham 1992; Pattnaik et al. 1997). Cinnamic aldehydes, linalool, alkaloids and phenols were responsible for the antibacterial activity of lemongrass (Onawunmi et al. 1984; Moleyar and Narasimham 1992; Pattnaik et al. 1997; Hindumathy 2011). It is more probable that the antibiotic activity of lemongrass is a result of the combined actions of its components rather than a single constituent (Ekpenyong et al. 2015). Table 2 shows the biological activities of lemongrass as well as the constituents

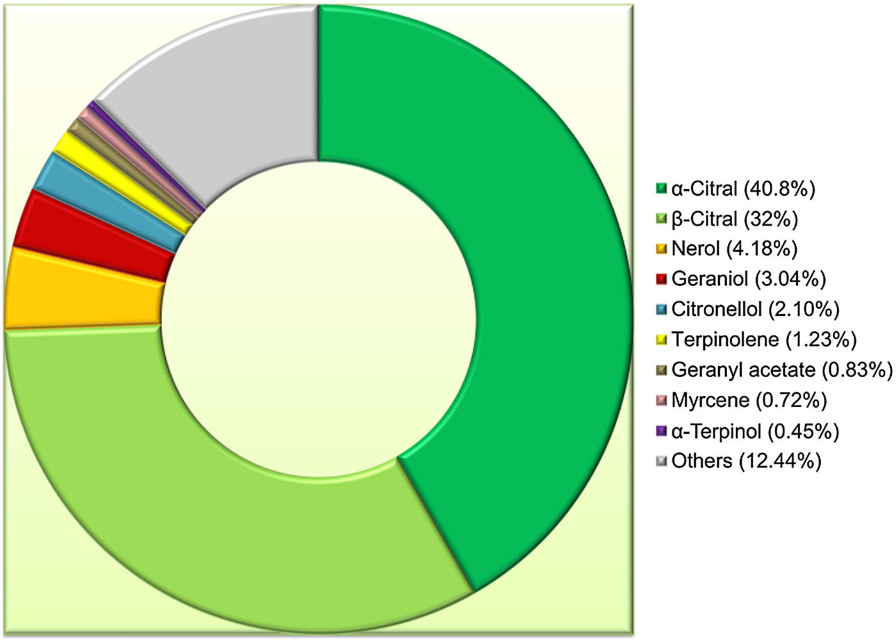
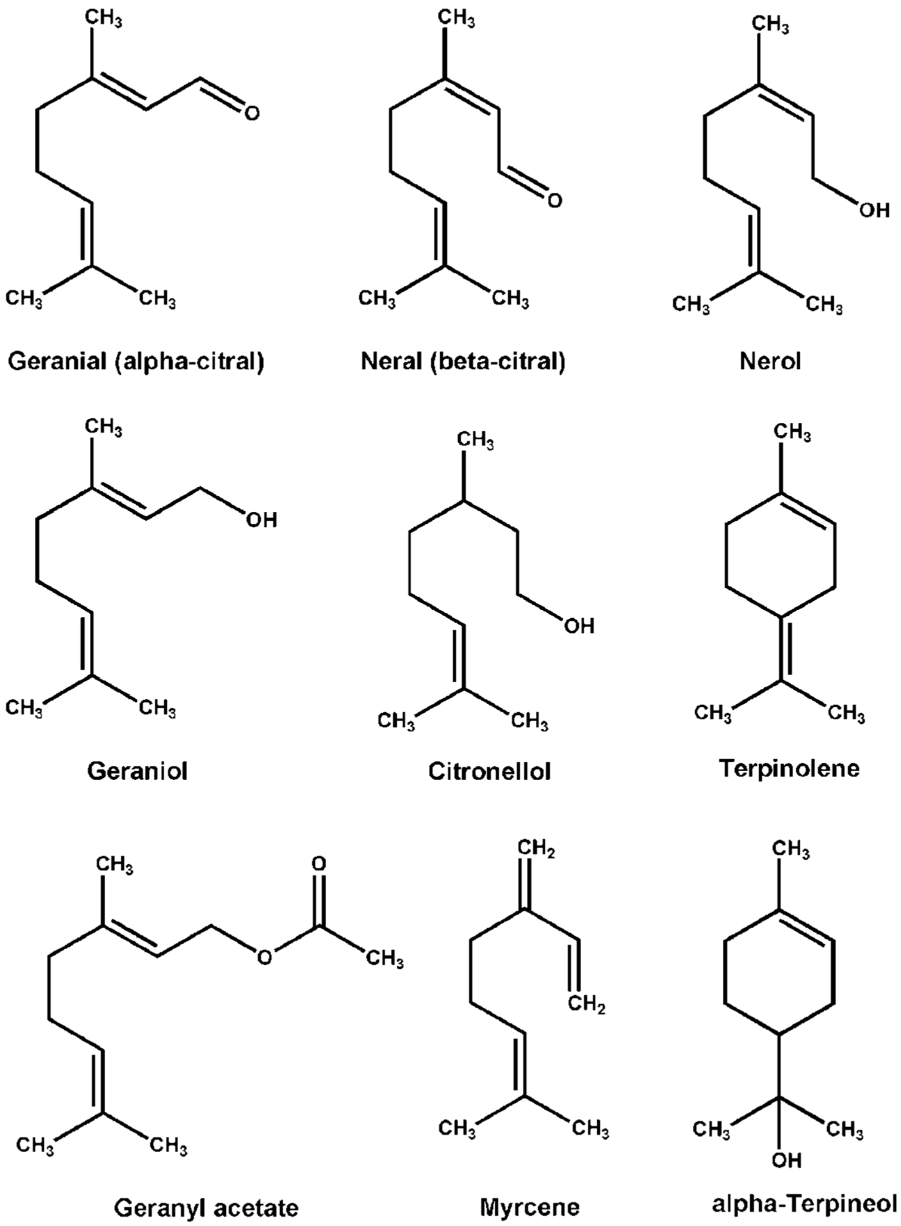


Fig. 4 Proportion of major constituents in lemongrass essential oil. (Drawn by data from Saleem et al. 2003a, b)

Fig. 5 Chemical structure of major constituents in lemongrass essential oil



for those activities reported by the researchers over the years.

Lemongrass has shown a number of other important properties including but not limited to anti-tumor, anti-carcinogenic (Zheng et al. 1993; Suaeyun et al. 1997), anti-mutagenic (Vinitketkumnuen et al. 1994), anti-amoebic (Blasi et al. 1990), anti-diarrhoeal (Tangpu and Yadav 2006), anti-filarial (Suresh and Raj 1990), larvicidal and ascaricidal (Chungsamarnvart and Jiwajinda 1992). However, its potential in materials science applications, as an abundant source of cellulose, has sparked scientific interest in recent years. These are discussed in the next sections.

Table 2 Different components of lemongrass and their biological activities

Biological activity	Components	References
Analgesic	Essential oils, flavoniods, alkaloids	Lorenzetti et al. (1991) and Bone and Mills (2013)
Antidiabetic	Essential oils	Souza et al. (2003)
Anticarcinogenic	Essential oils, flavoniods	Yaskawa et al. (1990), Elangovan et al. (1994) and Bone and Mills (2013)
Anti-inflammatory	Essential oils, tannins, saponins, flavoniods	Bone and Mills (2013)
Antimicrobial	Essential oils, tannins, flavoniods	Kishore et al. (1993), Mishra and Dubey (1994), Inouye et al. (2001), Liu et al. (2003), Bankole et al. (2005) and Bone and Mills (2013)
Antinociceptive	Essential oils	Lorenzetti et al. (1991)
Antioxidant	Essential oils, tannins, flavoniods, vitamins, phenols	Abd-El Fattah et al. (2010), Bharti et al. (2013a) and Bone and Mills (2013)
Antipyretic	Flavoniods, alkaloids	Bone and Mills (2013) and Ekpenyong et al. (2015)
Astringent	Tannins, saponins, alkaloids	Bone and Mills (2013)
Aromatherapy	Essential oils	Buchbauer and Jirovetz (1994) and Bone and Mills (2013)
Cardio-protective	Vitamins	Ekpenyong et al. (2015)
Cell signaling and transport	Minerals	Ekpenyong et al. (2015)
Diuretic	Essential oils	Bone and Mills (2013)
Hematological	Essential oils	Ekpenyong et al. (2015)
Hemodynamic	Minerals	Ekpenyong et al. (2015)
Hypocholesterolemic	Essential oils, saponins, flavoniods	Oakenfull and Sidhu (1990) and Bone and Mills (2013)
Hypoglycemic	Essential oils, tannins	Ekpenyong et al. (2015)
Hypotensive	Essential oils	Ekpenyong et al. (2015)
Insecticide repelling	Essential oils	Lima et al. (2009)
Neuropharmacological	Essential oils, alkaloids, minerals	Koo et al. (2003), Bone and Mills (2013) and Tayeboon et al. (2013)

Fields of application

Application of lemongrass as a cellulosic material

Adsorption of metal ions and dyes

As cellulosic materials exhibit good adsorption properties, lemongrass has been used as a bio-absorbent material for different metal ions and dyes. *Cymbopogon citratus* has been reported to adsorb Cu^{2+}, Ni^{2+}, Pb^{2+}, Cd^{2+} and Zn^{2+} (Zuo et al. 2012; Lee et al. 2014; Sobh et al. 2014; Hassan 2016) whereas the West Indian lemongrass, *Cymbopogon flexuosus*, was also found quite effective for removal of As^{3+} and Cr^{4+} from aqueous solution (Jha and Kumar 2017). For absorbing metal ions, lemongrass has been dried and crushed into powder in most cases for use as the absorbent material (Lee et al. 2014; Sobh et al. 2014). In addition, there are examples of considering the whole plant in the adsorption process (Jha and Kumar 2017). Formation of the smaller particle resulted in greater adsorption capacity, compared with 93% ion removal using the powder form of the lemongrass plant (Sobh et al. 2014).

For the dye adsorption processes, more intensive thermal treatment (500 °C) at muffle furnace (as illustrated in Fig. 6) has been reported to produce lemongrass ash for use as the absorbent. The results showed that more than 90% dyes were adsorbed onto lemongrass by 0.4–0.6 mg/100 ml adsorbent dose, indicating the true potential of this material (Singh 2014). More importantly, the isotherm models of

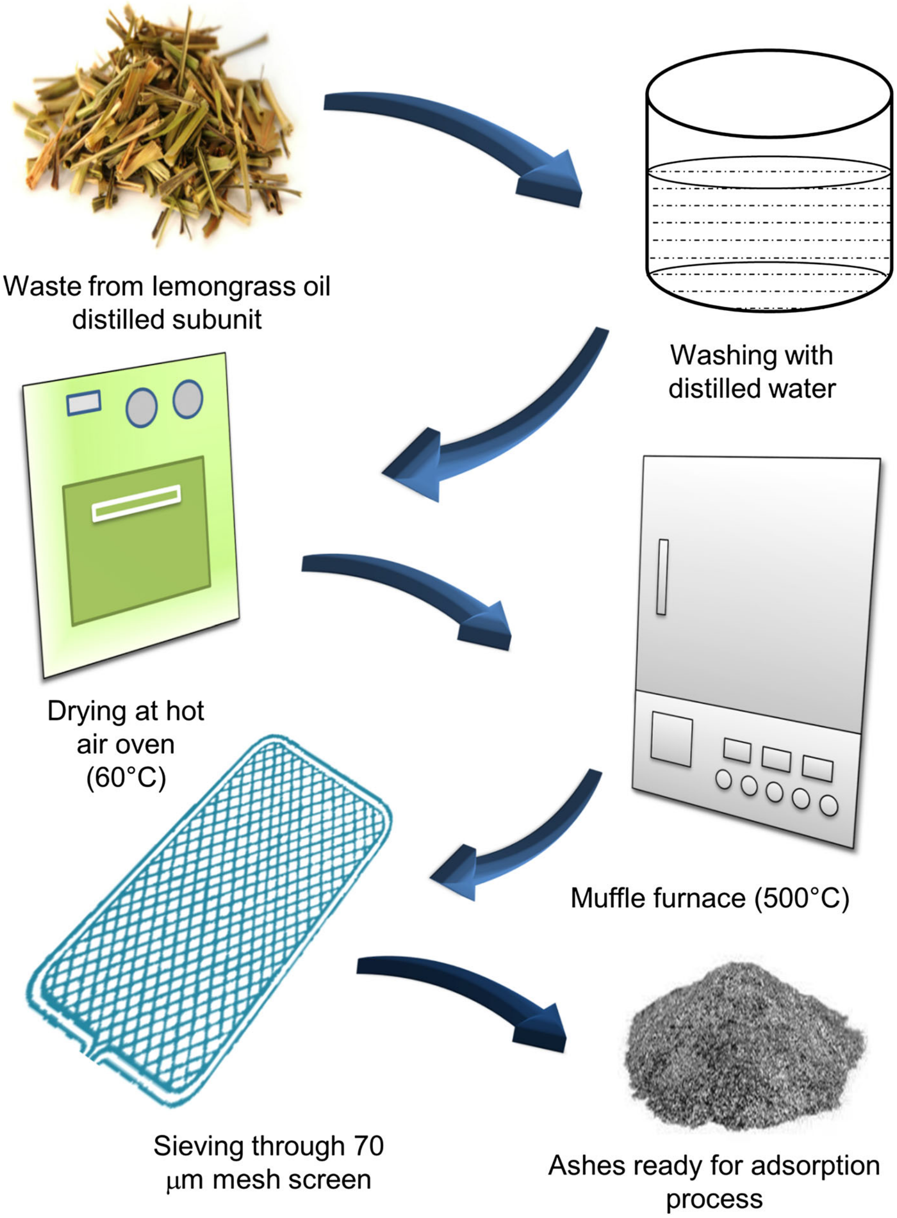


Fig. 6 Preparation process flow of ashes from lemongrass for dye adsorption. (Drawn from the concept of Singh 2014)

adsorption suggest the mechanism as a chemisorption process which is stronger than physical adsorption processes (Lee et al. 2014). However, it should also be noted the removal of dye and metal ions were found highly dependent on process parameters like pH, the concentration of the ion or dye, and time duration (Singh 2014). In all cases, the solution pH was reported as a significant control point for the adsorption (Lee et al. 2014; Singh 2014). Moreover, it was observed that the initial rate of adsorption was high rather than the later period that is likely due to the significant numbers of free sorption sites at the beginning stage of adsorption. More significant concentrations of the metal ion showed better adsorption too, as the higher number of ions were present initially to become adsorbed (Lee et al. 2014). When most of the sorption sites were saturated, the adsorption rate slowed down. However, for metal ion adsorption, the most effective adsorption was reported at 1 g/L bio absorbent concentration over which no significant increase in adsorption obtained (Lee et al. 2014).

In a study of dye adsorption, waste lemon grass was collected from the lemongrass oil distillation subunit and reformed to ash to examine its adsorption capacity to methylene blue dye (Singh 2014). Almost half of the dyes from the solution were adsorbed to the lemongrass ash in the first 90 min where around 40% was adsorbed in the first 40 min. Adsorption of dyes increased with the increase of the lemongrass adsorbent dose, pH and contact time. Similar to the adsorption behavior of metal ions, a higher initial concentration of dyes also resulted in better adsorption due to the availability of absorbent sites. Figure 7 shows variation in dye removal with respect to each of contact time, adsorbent dose, pH and initial dye concentration when the other parameters were kept constant (Singh 2014).

Production of paper pulp

Several species of grasses have already been examined for pulping and papermaking (Madakadze et al. 1999, 2010; Pahkala et al. 1999; Dutt et al. 2012). Lemongrass that is rich in cellulose has shown its potential to become a raw material for paper industries (Kaur and Dutt 2013; Kamoga et al. 2015). Figure 8 illustrates a manufacturing process of pulp and paper from lemongrass. Like other pulp making raw materials, lemongrass is cut into chips (15–25 mm) before delignification. The cooking of the chips of lemongrass was reportedly performed at 130–170°C for 1–3 h in presence of alkali and anthraquinone. The cooked material was washed, screened through a vibratory flat screen (0.15 mm pore size) and taken to beating operation before the sheet forming process through rollers (Kaur and Dutt 2013).

Lemongrass and Sofia grass have been used for the production of chemical grade pulp where lemongrass (*Cymbopogon Flexuosus*) showed better mechanical strength properties than Sofia grass, which is also a *Cymbopogon* species (*Cymbopogon Martinii*) renowned as the source of Palmarosa oil (Kaur and Dutt 2013). Moreover, the freeness of pulps, which is a measure of how fast the water can drain from samples, was low in case of lemongrass pulp compared to conventional wood pulps (Kamoga et al. 2015). This is probably because of more open spaces in fibrils than wood pulps due to the presence of short and broken fibres enhancing the surface area and resulting in higher absorption capability. Canadian Standard Freeness (CSF) is a measurement of freeness that is directly related to the energy requirement of paper industries. Figure 9 shows CSF values of

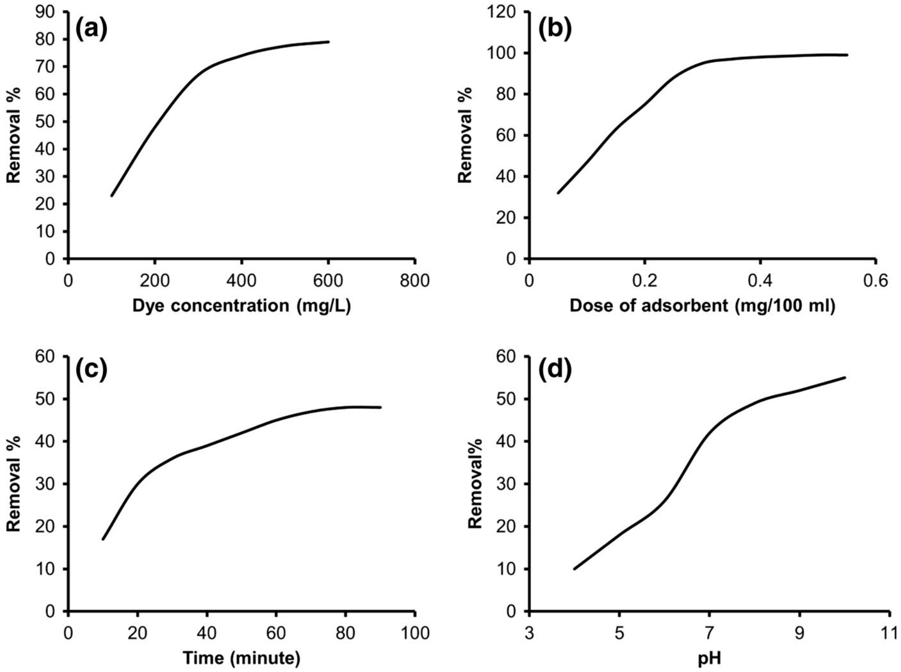
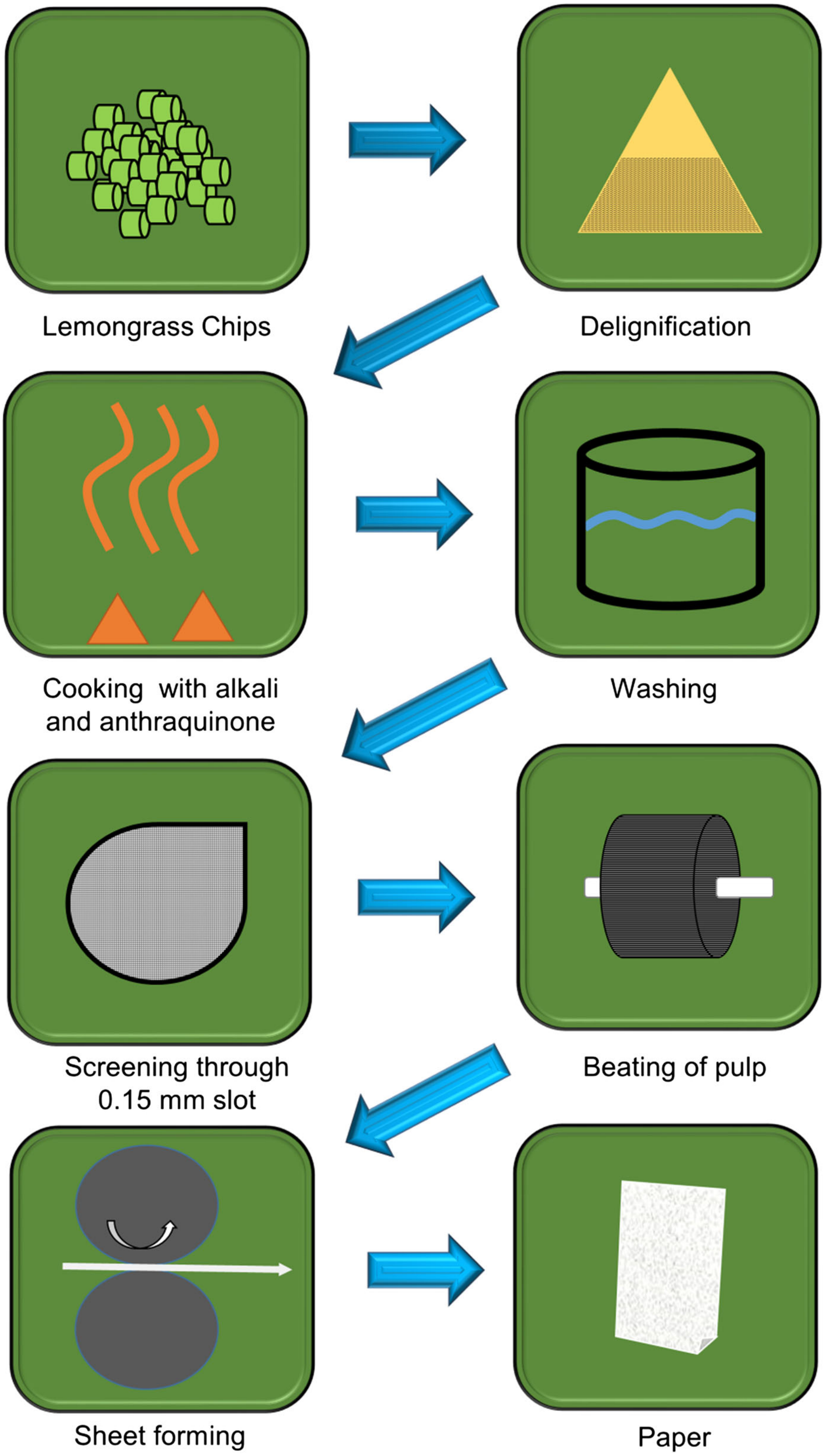


Fig. 7 Effect of individual parameters **a** dye concentration, **b** dose of adsorbent, **c** time and **d** pH on dye removal % by lemongrass ash when all other parameters were constant. (Redrawn from Singh 2014)

Fig. 8 Flow diagram for manufacturing pulp and paper from lemongrass. (Drawn from the concept of Kaur and Dutt 2013)



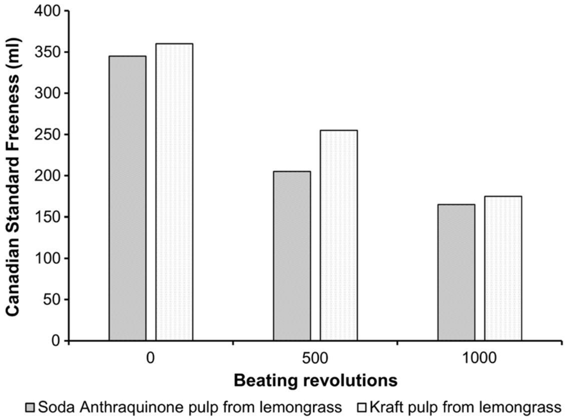


Fig. 9 Canadian standard freeness of *Cymbopogon nardus* pulps after beating revolutions. (Produced by data from Kamoga et al. 2015)

Cymbopogon nardus pulps prepared through two different methods. The soda-anthraquinone pulping was done by different alkali concentrations (10–25%) at temperature ranges from 100 to 160 °C for 1 h with 0.1% of anthraquinone concentration. Kraft pulping, the second pulping method was performed in 10–25% sulphidity with the same temperature range with same time duration. The CSF values were observed around 200 ml only after 500 and 1000 beating revolution whereas in general, 5000–6000 beating revolutions are required in industries to acquire 200 ml Canadian Standard Freeness (CSF) from wood pulps (Kamoga et al. 2015). This indicates the tremendous potential of lemongrass in this field in the future by consuming less energy and cost at an industrial scale.

Application as a composite material

The most recent application of lemongrass has been reported in the composite field, where lemongrass has been used as a reinforcing material for thermoplastic composite. Bekele et al. introduced lemongrass composite prepared from lemongrass flour (150–850 µm in particle size) in a combination of high density polyethylene (HDPE) with the presence of maleic anhydride grafted polypropylene (MA-g-PP) as a coupling agent (Bekele et al. 2017). The HDPE was used as matrix material where composites were prepared using varied lemongrass content from 10 to 50%. Figure 10 shows the process of producing a composite in that experiment where both modified (immersed in 0.5% Ca $(OH)_2$ for 6 h) and unmodified flour were used. Lemongrass flour was blended with HDPE and MA-g-PP in a counter rotating twine hot-press mixer at 175 °C. Finally, the blend was cast between two stainless steel plates to prepare the composite and it was found that reinforcing lemongrass significantly increased the mechanical properties of composites especially when modified one was used. The tensile strength of the composites (22.0 MPa for modified and 20.0 MPa for unmodified lemongrass) was observed higher than the control HDPE (19.4 MPa) when 10% fibre was added (Bekele et al. 2017). However, with further increase of fibre content, tensile strength decreased (around 13–15 MPa for 50% fibre content) due to weak interaction between fibre and matrix interface (Bekele et al. 2017).

Lemongrass EO has also been used to produce biocomposite films in combination with chitosan and starch through the sol–gel mixture. That method also involved mixing and casting followed by an ageing process. The SEM images of the produced bio-film discovered the homogeneous surface structure. Since the tensile strength of that film was not reported (Pandharipande and Katekhaye 2017), there is no indication of the suitability of the process used in that study.

Production of bio energy

There are a few investigations into the production of bioenergy from lemongrass. Figure 11 illustrates the flow diagrams of manufacturing bio oil and bio gas from lemongrass described in separate reports (Alfa et al. 2014; Madhu et al. 2017). In case of bio oil production, *Cymbopogon flexuosus* was dried and crushed then passed through the pyrolysis chamber in a fluidized bed reactor under the nitrogen atmosphere (Madhu et al. 2017). At best, 50.6 wt% bio-oil was achieved at 450 °C where the oil consists of a 22% water and around 40% of oxygen. The heating value of the produced bio oil (19.4 MJ/Kg) was reportedly higher than that of cotton shell, palm shell and garlic stem in that study. However, further research is required on this bio oil to compete with the industrial grade oils, as the current industrial oils have more than double heating value compared to the produced bio oil (Madhu et al. 2017).

The other thermal processing methods of producing bio energy like grate combustion and gasification have not been reported with lemongrass yet. Anaerobic

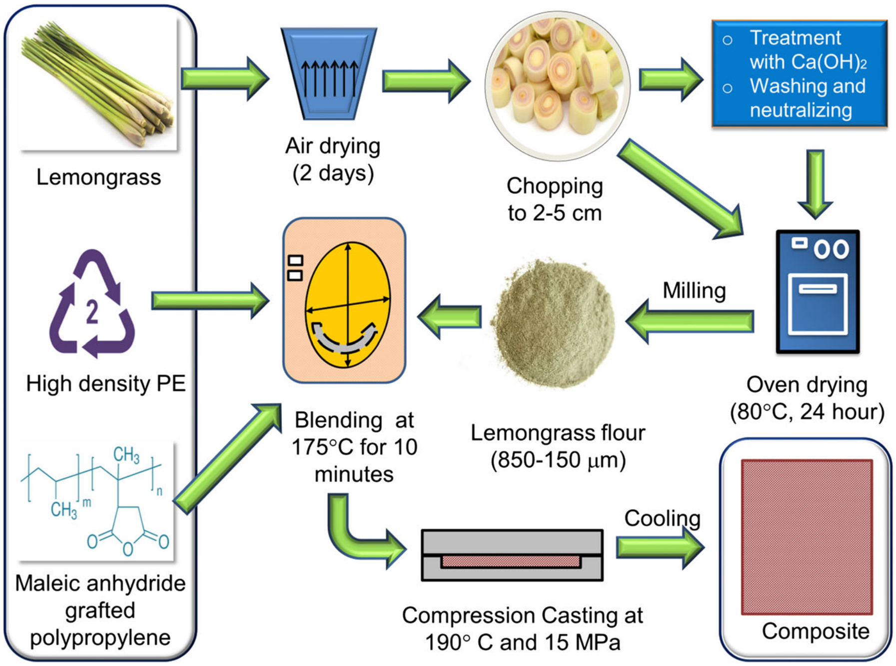


Fig. 10 Process flow of manufacturing composite from lemongrass and high density polyethylene in presence of maleic anhydride grafted polypropylene. (Drawn from the methodology of Bekele et al. 2017)

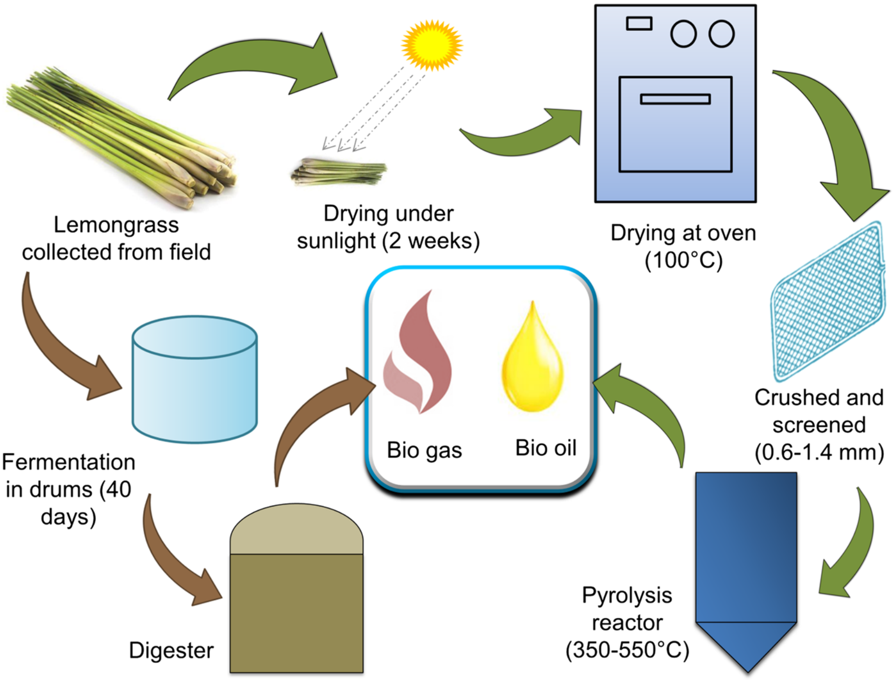


Fig. 11 Process flow for producing bio oil and bio gas from lemongrass through pyrolysis and anaerobic digestion respectively. (Adapted from Alfa et al. 2014; Madhu et al. 2017)

digestion, the biochemical process of producing energy has been reported where a smaller amount of bio gas was obtained from lemongrass compared to other two natural elements: cow dung and poultry dropping (Alfa et al. 2014). Moreover, there was a big difference in the pre-fermentation periods of the materials (40 days for lemongrass, 15 days for other two), as the plant material did not pass through any digestive systems like the cow dung and poultry dropping. However, the quality of bio gas obtained from lemongrass was reportedly better. For instance, the bio gas from lemongrass had left the smaller amount of total solids (TS), volatile solids (VS), volatile fatty acid (VFA), total ammonium Nitrogen (TAN), chemical oxygen demand (COD), orthophosphates, *E. coli* and *Enterobacteriaceae* counts in its solid and liquid residues (Alfa et al. 2014).

Production of silica

The current manufacturing process of silica throughout the world is expensive and energy consuming where furnace temperature ranges from 1300 to 1500 °C (Srivastava et al. 2013). Alongside the applications stated above, two different methods of obtaining silica from lemongrass have been reported (Firdaus et al. 2015, 2016). Figure 12 shows the process flow of the described methods, where one involves an acid leaching treatment while the other illustrates silica production directly by calcination. In both cases, the considered lemongrass was cultivated in heavy clay soil that had a high content of silica. The collected plant was washed, dried and ground and passed through a 20-mesh screen before doing any other treatments.

In their first method, hydrochloric acid leaching was performed on lemongrass particle at different temperatures (33–110 °C) followed by a thermal combustion at 600 °C in muffle furnace, which resulted in several metal oxides (CaO, MgO, P_2O_5, Fe_2O_3, K_2O) along with SiO_2 (Firdaus et al. 2015). Among the different acid leaching temperatures, though the crystallinity of lemongrass ash (which was 55% before acid leaching) decreased to 31% at 37 °C, it significantly increased to around 73% at 110 °C. In the other report, direct calcination of ground lemongrass was done without any acid pre-treatment. The calcination temperatures ranged from 400 to 700 °C with a combustion at 525 °C (Firdaus et al. 2016). The crystallinity of lemongrass ash increased from 36% (without calcination) to at best 63% (calcination at 700 °C) in that investigation. In both processes, siloxane (Si–O–Si) and silanol (Si–OH) groups were evident in lemongrass ash in all ranges of application temperatures that rely on lemongrass for silica production. Nevertheless, of the two methods, the acid leaching could be highly effective in terms of silica production, than the combustion method due to its high percentages of silica content in the end product. For example, acid leaching at 110 °C followed by thermal combustion at 600 °C produced more than 98% of silica and a very small amount of other metal oxides. But in direct combustion method, among all the metal oxides, the

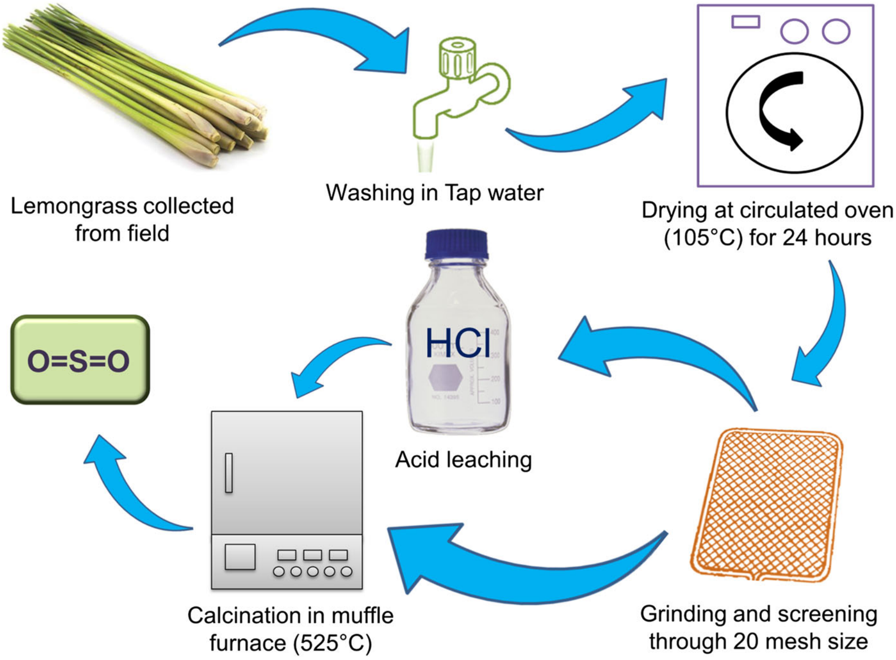


Fig. 12 Production of silica from lemongrass with and without acid leaching. (Drawn from methodologies of Firdaus et al. 2015, 2016)

highest amount of silica was reported as only 24% at 400 °C.

Applications of lemongrass on basis of biological activities

Therapeutic uses

Lemongrass is widely used to heal many medical conditions due to its ability for producing secondary metabolites (Kumari et al. 2009; Oloyede 2009; Garg et al. 2012; Mirghani et al. 2012). Up to now, lemongrass has been used for numerous medical purposes such as preventing platelet aggregations (Tognolini et al. 2006), treating diabetes (Mansour et al. 2002), dyslipidemia and gastrointestinal troubles (Carlini et al. 1986; Negrelle and Gomes 2007), fever, flu and pneumonia (Negrelle and Gomes 2007) and anxiety (Xaio 1983). This plant is also used in Nigeria as an antipyretic and anti-protozoan agent for treating Malaria and related symptoms (Olaniyi et al. 1975; Tchoumbougnang et al. 2005). There are extensive reports that confirmed the influential character of constituents of lemongrass on pain sensitivity, behavior, hormone releases and neurotransmitter signaling (Seth et al. 1976; Koo et al. 2003; Gasser et al. 2006; Blanco et al. 2009). Moreover, it has also been reported that lemongrass extracts possess anticonvulsant and anxiolytic effects (Blanco et al. 2009; Sforcin et al. 2009). This grass is also proven effective for weight loss without interfering with the activity of liver enzymes (Batubara et al. 2015).

Lemongrass also has hypolipidemic, hypoglycemic and hypocholesteremic properties which are very much connected with heart conditions (de Melo Junior et al. 2002; Adeneye and Agbaje 2007; Agbafor and Akubugwo 2007). Low-density lipoproteins (LDL) and very low-density lipoproteins (VLDL) are also known as bad cholesterol because these enhance fatty build-ups and narrow the arteries resulting affecting the heart condition. In contrast, high density lipoproteins (HDL) are the good cholesterols that carry the LDLs from arteries to the liver and lower the risk of heart diseases. The ability of lemongrass to raise the HDL and limit LDL and VLDL (Fig. 13) is hence a very significant finding, reported by Adeneye and Agbaje (2007).

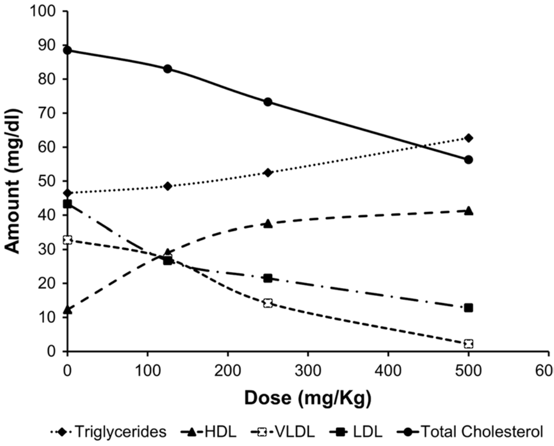


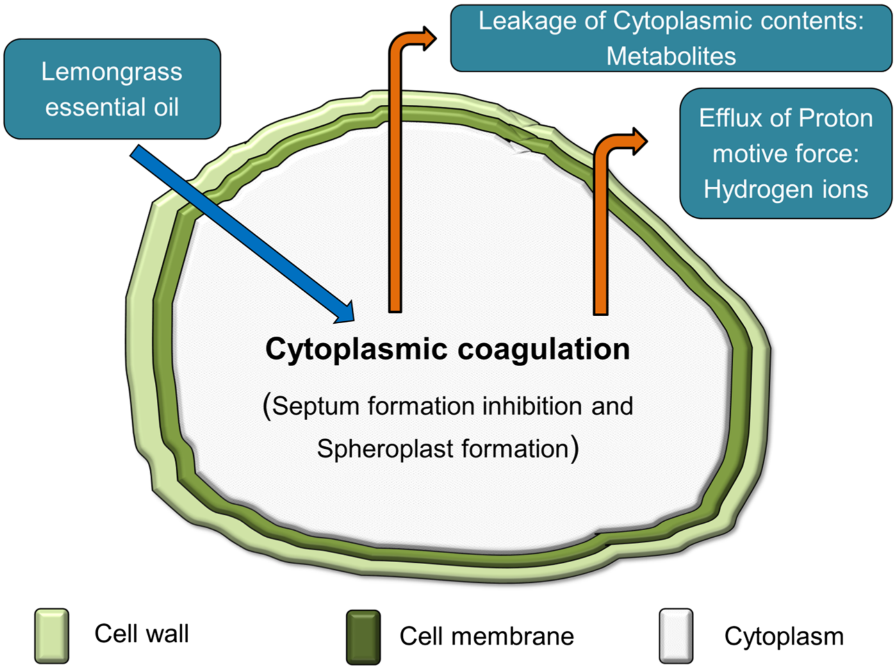
Fig. 13 Effect of lemongrass leaf extract doses for 42 days on Triglycerides, High density lipoprotein (HDL), Low density lipoprotein (LDL), Very low density lipoprotein (VLDL) and total cholesterol. (Drawn by data from Adeneye and Agbaje 2007)

Numerous applications of lemongrass and its EO are evident all over the world. Lemongrass tea and extracts are reported to be taken as an antipyretic, antispasmodic, sedative, diuretic, anti-inflammatory and analgesic compound (Leite et al. 1986; Souza et al. 1986), also to treat sore throats and empacho (Filipoy 1994), to increase the menstrual flow in the Philippines (Quisumbing 1951; Burkhill 1966), to heal wounds and bone fractures (Spring 1989), to treat diabetes (Mueller-Oerlinghausen et al. 1971), for lowering blood pressure, treating catarrh and rheumatism (Carbajal et al. 1989), to get relief from fever and severe headache (Rao and Jamir 1982) and to treat gastric troubles and cholera (John 1984), This leaf extract along with the extract from stems are also used as a diuretic and renal antispasmodic (Locksley et al. 1982). There are substantial reviews available on different medicinal applications of lemongrass and their scientific basis (Ravinder et al. 2010; Shah et al. 2011; Ranade and Thiagarajan 2015).

Application in food preservation

The antimicrobial activities of EO of lemongrass against microbes are well reported. Notably, the activity of lemongrass EO was found more beneficial than other EOs against 12 important bacterial species (de Silveira et al. 2012). The probable antibacterial mechanism of lemongrass EO on the cytoplasmic cell is illustrated in Fig. 14 that shows the EO induces cytoplasmic coagulation which includes spheroplast

Fig. 14 Probable antibacterial mechanism of lemongrass essential oil for food preservation. (Redrawn from the concept of Ekpenyong and Akpan 2017)



formation as well as preventing septum formation. It flows out the intra-cellular hydrogen ions resulting in immobility and mortality of bacterial cell (Ekpenyong and Akpan 2017).

Moreover, the real advantage of lemongrass EO is its action against both gram positive and gram negative bacteria (Naik et al. 2010). Lemongrass was found effective against fungi (Mishra and Dubey 1994; Paranagama et al. 2003) and several bacteria including *E. coli and Salmonella Enteritidis* (Raybaudi-Massilia et al. 2006; Moore-Neibel et al. 2012). This EO has reportedly inhibited the germination of several key postharvest pathogens like *Colletotrichum coccodes*, *Botrytis cinerea*, *Cladosporium herbarum* and *Rhizopus stolonifer* that are significant for food preservations (Tzortzakis and Economakis 2007). It has been reported that lemongrass increases the life of different fruits like guava (Murmu and Mishra 2018) and cucumber (Omoba and Onyekwere 2016) as well as fruit juice (Tyagi et al. 2014). It was also found effective in preserving processed foods like yoghurt (Abd-El Fattah et al. 2010), cheese (Belewu et al. 2012), other dairy products (Abd-El Fattah et al. 2010) as well as bread, cake and bakery products (Guynot et al. 2003; Suhr and Nielsen 2003). Although lemongrass has potential features to become a bio preservative for food storage, as lemongrass is a natural flavour complex (NFC), it has the potential to become toxic, especially at high level of exposure to the gustatory or olfactory systems (Smith et al. 2005). These have been reviewed comprehensively by Ekpenyong et al. in different articles (Ekpenyong et al. 2015; Ekpenyong and Akpan 2017).

Application in cosmetics

The biological activities of lemongrass constituents are not only the key for applications in medicines and food science but also important for cosmetics applications. Citral, the main component of lemongrass oil is considered for producing β-ionone which provides rose aroma with low concentrations and thus significant for application perfumery industries. The EO of *cymbopogon* genus has commercial usages in palmarosa oil, perfume material and soap aroma (Davis et al. 1983). There are a number of lemongrass products available in the cosmetic field with patented formulas in combination with lemon balm oil and glycerol (Yongtian et al. 2015). In a particular patent, bacteria that arises from the pod of lemongrass generates pleasing and refreshing smell and therefore become a source of perfume (Yuhua et al. 2014). The antibacterial activity of lemongrass has the potential to be used as disinfectants or liquid antibacterial soaps depending on the activities of gram positive and negative bacteria (Mosquera 2016). Actions of the lemongrass EO on the pathogen and bacteria suggests its likelihood to treat human skin problems like acne (Lertsatitthanakorn et al. 2006; Melo et al. 2015). It has been shown that the EO of lemongrass has the ability to repel insects, which opens the opportunity to be used as a repellent lotion (Lima et al. 2009). The antioxidant property of this oil is very significant for cosmetic industries as this activity can be used to prevent several dermal diseases that are resulted from oxidative stress (Pereira et al. 2009). Moreover, as the oxidative stress is related to chronic degenerative diseases that cause early ageing, this material can be used as anti-ageing cream as well (Saraí et al. 2006). The bioactivities of lemongrass that are correlated with its potential cosmetic activities have been also comprehensively reviewed in the recent year (Mosquera 2016).

Agriculture and farming

Although the application of lemongrass in agriculture and farming is associated with its biological activities, this is a relatively new area of research and only a few studies have been reported. The roots of lemongrass have been used for reinforcement of a landslide-affected soil in India. It was found that the shear strength and unconfined compressive strength of natural soil was approximately doubled by only 4% of lemongrass roots (Gobinath et al. 2015). It was found also very effective with 50–50% combinations with cotton waste in the cultivation of the mushroom (Mumtaz et al. 2016). In a different study, lemongrass EO was found prospective not only in governing isariopsis spot in grape leaves and mildew but also increasing productivity grape cultivation (Maia et al. 2014). In addition, the ethanolic extract from lemongrass in combination with parthenium was reportedly an effective in citrus scab (*Elsinoë fawcettii*) management (Rehman et al. 2016). Lemongrass extract has shown improvement in germination of rice seed and seedlings, as well as their vigour index, and it was effective for regulating seed-borne rice fungi (Rahman et al. 2014). Furthermore, the EO of lemongrass was tested as poultry feed by including it in broiler feed in Nepal. The results suggested that inclusion of EO in broiler chicken can increase weight gain, while reducing mortality and the broiler harvesting period (Tiwari et al. 2017).

Implications and future study

Lemongrass is an abundant source of natural cellulose that possesses an enormous potential to be utilized as a prospective raw material for materials science. While there has been comprehensive research on lemongrass over the decades, there is much scope for future research on this material in different dimensions.

The research on adsorption behaviour of lemongrass is still in the embryonic stages and further investigations are required to assimilate the findings. Though there are a few reports on lemongrass and its potential adsorption properties (Lee et al. 2014; Singh 2014), identifying adsorbent characteristics towards common textile based dyes has not been investigated yet. Our current research on preparing membranes from lemongrass (unpublished results) showed well distributed pores (Fig. 15) throughout the surface of lemongrass. This is highly noteworthy as the porosity of the surface has led into better adsorption properties (unpublished results) and thus enhancing the suitability of the material for the membrane, which might be a future area of research.

The results from the initial research on paper pulp fabrication are very promising, and this fabrication provides an energy saving processing route for the paper industry (Kamoga et al. 2015). However, more detailed and systematic research is required for the bulk production. In composites, the mechanical properties of lemongrass-HDPE composites were found higher than the HDPE material which is a remarkable finding (Bekele et al. 2017). However, further research is warranted to understand the reasons behind the mechanical properties, the potential and impact of this material in composites. While production of bioenergy is a highly interesting research area and more works are emerging with natural lignocellulose biomass, not much research was reported on lemongrass in this regard. Although lemongrass has a considerable amount of fibrous content and there are reports of successful dissolution of lignocellulose materials (e.g. wheat straw and bagasse) in different solvents (Chen et al. 2014; Domínguez de María 2014; Li et al. 2015), no attempt was made to regenerate the lemongrass fibre through a spinning process.

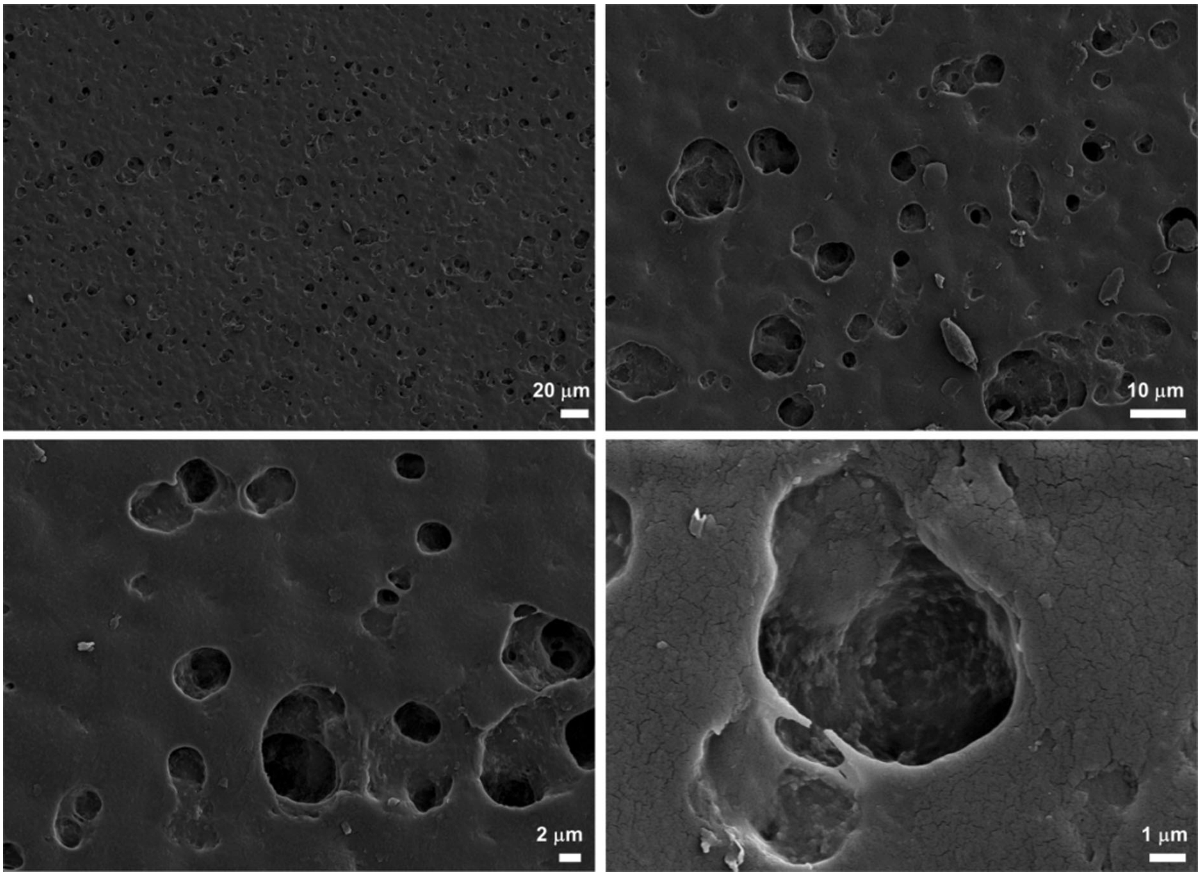


Fig. 15 SEM images of lemongrass membrane surface at different magnifications (unpublished results)

Additionally, regeneration of packaging film from lemongrass can be a great direction of research as this material has antibacterial properties that can lead to a new way for the bio-preservation of food materials. Therefore, investigating lemongrass potential from material aspect might be the next generation precursor for biodegradable film, fibres, membranes and an antibacterial food packaging.

In contrast, research on the biological activities of lemongrass is already extensive. Nevertheless, until now most of the research concerning lemongrass in medical aspects has been conducted with animal subjects. Therefore, there is much to be proved from the standpoint of human cases. The probability of toxicity of lemongrass EO in food preservation might be another concern to look for in future research.

Conclusion

Lemongrass constitutes an abundant source of cellulose, hemicellulose and lignin and has an enormous potential as a raw matter for novel materials fabrication. However, the research in materials engineering applications is still in its infant stage. Until now the studies on lemongrass have mostly focused on its biological activities. However, there are a few encouraging research works conducted in recent years, which revealed its potential as the cellulosic material. It had been successfully used as the adsorbent for metal ions, dye and as a raw material for producing pulp and paper. It has also been introduced as a reinforced material in composites and has been used to produce bioenergy and silica. It is thus significant to find the engineering application for lemongrass to ensure the quality of commercial demands. Using lemongrass in diverse research areas suggests its enormous potential to become a new generation of raw material in the near future. Hence, collective effort from material researchers is required to consider lemongrass as the "spectacular biopolymer".

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