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Degumming methods for bast fibers—A mini review

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ABSTRACT

Bast fibers, such as ramie, hemp, flax and kenaf, are natural fibers with high specific stiffness and strength that have gained increasing attention in recent years. Bast fibers are advantageous in terms of their biodegradability and abundance in nature, making them promising candidates for automotive industry, structural composites, pulping and textile applications etc. There is a strong desire from industry for a high yielding natural cellulose fiber alternative to cotton due to the high volume of irrigation water, intensive use of pesticides, high cost and climatic conditions required to grow cotton. Before converting bast fibers into value-added products, degumming is a necessary step to separate cellulose and non-cellulose parts. Due to environmental consideration, degumming methods are developing to biodegradable green processes with high degumming efficiency. All works discussed in this review aim at revealing degumming methods for bast fibers and the potential for the design of eco-efficient processes. Objective appraisals toward the methods are discussed here, opening straight-forward access to the new chemicals and materials in the degumming industry.

1. Introduction

Globally appealing for sustainable development, industrial and academic fields are prompted to produce high-value materials that follow environmental preservation interests. To develop recycling technologies to supplement non-renewable sources research has been undertaken. This trend has led to the resurrection of natural fiber. Natural fiber refers to animal fibers (like wool and silk) and plant fibers (from stems, seed and leaves etc.). This article will focus on bast fibers and will examine properties and the early-stage processing methods that have been developed to remove them from their plant based composite structure.

Bast fibers, including hemp, sisal, jute, ramie, and kenaf, have many properties making them good candidates for various industries. The high stiffness, low elongation and reasonable tensile properties (Rehman et al., 2019) of bast fibers enable their utilizations in many fields, such as reinforcing organic composites in high-performance material applications (Del Masto et al., 2017;Yang et al., 2021), forming automobile parts in transportation industry (Li et al., 2010), and building applications for external walls and ceilings (Müssig, 2010). There are other countless desirable properties of natural plant fibers, which include low cost, low density, less skin and respiratory irritation to the human body and enhanced energy recovery (Sgriccia et al., 2008). The superior properties make bast fibers also good candidates for clothing (Clarke, 2010a, 2010b; Varshney and Bhoi, 1988).

Most of the applications were based on the fibroid form of the bast plants, thus the first step of making them into high-value products is to extract the fibers from the plant bark. This degumming process can be defined as the breaking of bonds among cellulosic fibers and the non-cellulose matrix.

This review covers the structure and composition of bast fibers, the component gum matrix and different degumming methods for fiber extraction.

2. Structure and composition of bast fibers

Conventionally grown bast fiber plants include flax, hemp, jute, ramie and kenaf. Flax originates from the Mediterranean and Southwest Asia (Christophe Baley et al., 2020). It belongs to the Linaceae family which has 13 genera and 300 species (Bourmaud et al., 2020). A flax stalk has a height of 0.8–1.2 m and a diameter of 4–5 mm (Pisupati et al., 2021). Instead of being used as textile materials, flax fiber reinforced composites are widely explored. Flax is well known for its use in linen and textiles. Hemp originates from central Asia, and it is now widely cultivated throughout the world. It is a member of Cannabaceae

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family. The growth of the hemp plant was heavily restricted until the low-tetrahydrocannabinol variety was explored in 1998 (Wimalasiri et al., 2021). Hemp plant ranges in length from 1.0 m to 2.5 m and diameter from 7 mm to 16 mm (Hammami et al., 2021). Every part of the hemp plant has value so there is a wide application in food, medicine, textile, and composites. Jute is from the family of Tiliaceae, it is mainly produced in Asian areas. The height and average diameter of jute is 2.5–3.5 m and 20 mm respectively (Sanivada et al., 2020). It is the most widely grown bast fiber because it is easy to grow, and it is recognized as the cheapest natural fiber (Saleem et al., 2020). Ramie is also called China grass due to the largest production (94 % in the world in 2014) in China (Cheng et al., 2020). It is a member of Urticaceae family. The ramie plant grows to 1.0–2.5 m in height and 4.5–10 mm in diameter. Ramie fiber is widely used in the textile industry (Rehman et al., 2019). Kenaf can be easily grown in different areas with various climate conditions. It is the specie of the Malvaceae family. Kenaf plant has a height from 2.5 to 4.0 m and diameter from 10 to 20 mm (Ramesh, 2016). It has good performance in reinforcing polymers to form biodegradable materials.

2.1. The structure of bast fibers

From a macro perspective, a complete bast fiber plant is composed of bark, fiber bundles, and xylem (Fig. 1a). Every component plays a vital role in the growth of the plant. As the outer part of the plant, the bark performs as a guard to protect the plant from internal moisture loss, damage from environmental conditions and bending. Fiber bundles, consisting of many single fibers, are located in the phloem under the bark. Bast fibers need to be stripped away from the phloem part. Fibers operate as carriages for cells. In the inner layer is the xylem matrix conducting system used to transmit water and other necessities throughout the whole plant, which forms shives after cutting (Charlet et al., 2007). A bast fiber plant has a hollow structure so there is a cavity in the center.

From a micro perspective, viewing the middle part of the plant, fiber bundles are composed of single fibers, which are connected by middle lamella (Fig. 1b). The middle lamella is a gathering of the gum, mainly including lignin, pectin and hemicellulose.

The individual fiber has a particularly complicated multi-layered cell wall and lumen structure. The multi-layered cell wall contains the primary and the secondary wall. The similarity between the two walls is that they contain cellulose, hemicellulose, lignin, wax and pectin. The cellulose has a spiral orientation while hemi-cellulose and lignin components spread randomly, thus forming a compound matrix. Compared with the primary wall, the secondary wall is thicker and more complicated. It is further separated into three layers: S1, S2 and S3 layers (Fig. 1c) (Michael George et al., 2014). The S1 layer protects the fiber from lateral scalability and maintains dimensional stability. The S2 layer is the thickest in the secondary wall, which holds 70–80 % of the fiber (Gorshkova et al., 2000; Zykwinska et al., 2008). Fibers in the S2 layer are responsible for the mechanical properties of the whole bast fiber. The S3 layer has the same responsibility as the S1 layer which is to stabilize cells by resisting hydrostatic compression. The lumen structure is formed by the innermost enclosed S3 layer (C. Baley, 2002).

Consequently, bast fibers naturally possess composite structures with individual fibers bonded by non-cellulose matrix (Kandimalla et al., 2016).

2.2. The composition of bast fibers

There are slight differences in the chemical composition of bast fibers. The discrepancy occurs in different varieties of the bast fibers or different parts of the same fiber (Michael George et al., 2014). The main components of a bast fiber include cellulose, hemicellulose, lignin, pectin and wax. External as well as internal factors exert influences on the proportion of the chemical components. External factors include ways for fiber extraction, while internal factors refer to the fiber age and source (Kiruthika, 2017). The chemical compositions of different bast fibers are shown in Table 1.

The chemical components are subdivided into cellulose and non-cellulose materials. Cellulose accounts for most of the fiber chemical components. The amount of cellulose has positive influences on the mechanical properties and application value of bast fibers (Reddy and Yang, 2005). Cellulose is a linear polysaccharide composed of repeating disaccharide units. 30−100 molecules of well-organized cellulose can form an elementary fibril with the thickness from 2 to 10 nm. The

Table 1
Chemical composition of different bast fibers (Michael George et al., 2014; Rehman et al., 2019).

Fiber type	Chemical composition (%)				
	Cellulose	Hemicellulose	Lignin	Pectin	Wax
Flax	60−81	14−19	2−3	1.8−2.3	1−2
Hemp	55−77	14−22.4	3.7−13	0.9	2
Jute*	51−84	12−20	5−13	0.2	1
Ramie	68.6−91	5−16.7	0.6−0.7	1.9−2	1−2
Kenaf	44−57	21	15−19	0.6	0.5

* Note: Jute is a seed fiber but has been included in the table for cross reference.

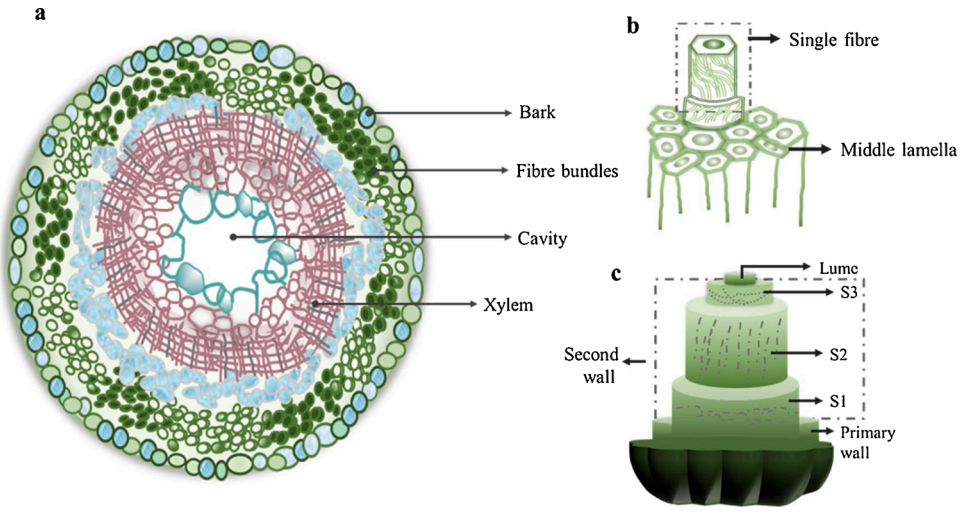

Fig. 1. (a) The cross-section model of a bast fiber stalk, (b) a bast fiber bundle and (c) model of a single fiber (Sadrmanesh and Chen, 2018).

combination of 10–50 single fibrils and hemicellulose is called micro-fibrillated cellulose. Micro-fibrillated cellulose units are then assembled with non-cellulose materials into complex structures, which are referred to as bast fibers (Kian et al., 2019).

Non-cellulose materials are also called gums, which include hemicellulose, lignin, pectin and wax. These materials work together to transfer nutrition and help to resist outside attacks on the fiber.

Hemicellulose is an integration of polysaccharides, which include glucose, arabinose, xylose, and mannose. The copolymers have lower molecular weights than cellulose and form nonlinear structures with less strength (Komuraiah et al., 2014). Therefore, hemicellulose contributes little to the mechanical property of the fiber. Hemicellulose has good hydrophilicity and it is readily biodegradable (Taj et al., 2007).

Lignin (Laurichesse and Avérous, 2014) forms in the process of water removal from polysaccharides (primarily xylose), which occurs in mature plants. It has a high molecular weight with aromatic structures and possesses a high percentage of carbon and hydrogen (Komuraiah et al., 2014). Thus it endows rigidity and mechanical stability to the plant. It also helps with water transmission through the fiber.

The flexibility of a bast fiber depends on the content of pectin. Higher amounts of pectin contributes to very soft fibers, which are unsuitable for industrial applications (Ridley et al., 2001). Wax (Kunst and Samuels, 2003) plays an important role in resisting dry conditions and microbial invasion of the fiber. It belongs to esters with long-chain fatty alcohols.

3. Degumming methods

Degumming is the process of removing the fiber from the bark composite structure. It also may be known as retting. Methods of fiber degumming have been divided into four categories: physical, semi-physical, chemical and biological. In practice most degumming processes are a combination of two or three of these categories to achieve better bast fiber qualities. Physical extraction involves applying mechanical forces to the straw to separated shives and fiber bundles. Semi-physical method aims to firstly break down intermolecular forces with the aid of physical treatments. The loosened matrix is then able to react with chemicals or bio-organisms. Chemical treatment aims at dissolving the non-cellulose components. Compared with physical or semi-physical extraction, chemical treatments, under appropriate experimental parameter settings, are more efficient and easier to produce ideal samples. There are still shortcomings of this treatment, in particular pollution to the environment due to disposal of by-products. There is continued research work looking for more environmentally friendly chemical degumming systems. These novel reagents are relatively more environmentally friendly and simple experimental processes. Enzymes and fungi are the two key methods for biological separation of bast fibers. These tend to be more environmentally friendly when compared with other methods.

3.1. Physical extraction

Physical extraction is a process of removing fibers from the bark and shives using only mechanical processing equipment. Machinery to do physical extraction is generally very large and the process involves multiple steps so is often factory based. Physically extracted fibers are often not subjected to further chemical or biological separation. However, they may have had some form of pre-treatment such as field retting or pre-treatment with chemical or biological methods. The separation of fiber bundles and shives purely depends on shearing, pressing or tearing forces. There are mainly three progressive steps for physical extraction: decortication, fiber cleaning and fiber opening. Decortication reduces the adhesion between shives and fiber bundles. The incompletely detached fiber-shive samples together with the dusty fiber bundles need to undergo further fiber cleaning processes to achieve further separation and dust removal. The separated clean fiber bundles will undergo fiber opening to get fine fibers or even single fibers. Most physical extractions save time, but the sample results are irregular, and the quality of fiber is only suitable for limited applications. Fiber breakage leads to poor separation and short fiber length, which makes fiber spinning difficult. Physical extraction methods are concluded in Table 2.

3.1.1. Decortication

Decortication is responsible for the initial formation of bast fiber bundles. The stalks are subjected to complex shearing forces in decorticators or by hand and come out ideally as two separate components: fiber bundles and shives. In reality a portion of shives are often still partially attached or entangled within the fiber bundles after decortication. The two products have efficient applications in industries. Instruments used for decortication include manual operation, blade crushers, hammer mills, roll crushers, ball mills, planetary decorticators and modified machines.

Bast fiber bundles, like hemp, were initially obtained by manual exfoliation from the stalks in China as early as 4000 BC (George et al., 2016). This is regarded as the oldest method for decortication. This process was then substituted due to the inefficiency. Manual operation

Table 2
Treating process and obtained fiber quality (average value) by different physical degumming methods.

Methods		Treated fiber	Obtained fiber quality (average value)	Reference
Decortication	Blade crusher	Cotton stalks	Particle diameter of 100−250 μm	(Luo et al., 2014)
	Hammer mill	Flax	Fiber yield at 96.4 %, fiber purity of 79.1 %, fiber length varies from 20−100 mm.	(Thakur et al., 2017)
	Roll crusher	Agave Americana plant	NA	(Hulle et al., 2015)
	Ball mill	Hemp	Core yield at 20.3 %	(Baker et al., 2010)
	Planetary-roll crusher	Hemp	Fiber yield at 30 %, fiber tenacity at 0.38 N/tex, fiber impurities at 2−4 %	(Hobson et al., 2001)
	Scutcher	Flax	Fiber loss at 5−50 % with one or two pairs of rollers, a fiber yield at 72 % for retted stems and 48 % for incomplete retted stems	(Akin et al., 2005)
Fiber cleaning	Step cleaner	Flax, hemp, jute, sisal, kenaf, abaca, or ramie	A fiber fineness of 2.5−15 tex can be achieved with a fiber length from 50−200 mm (Munder et al., 2005).	(Munder et al., 2005)
	Comb shaker	Flax	Fiber yield at 50 %	(Pecenka and Fürll, 2008)
	Opening cylinder	Flax, hemp, jute, sisal, kenaf, abaca, or ramie	650 kg of fibers can be fed in	(Munder et al., 2005)
Fiber opening	Carding machine	Unknown bast fiber	Fiber tenacity of 19.7−25.5 cN/tex, fiber elongation of 6.6−7.7 %, uniformity index varies from 65−77	(Göktepe et al., 2003)

now occasionally occurs in laboratories for small amounts of fiber.

The blade crusher is an old technology, which mainly consists of a high-speed motor and a group of blades (Fig. 2). The decortication effect is influenced by the blade type, blades gap, and the blade sliding angle (Andrianto and Fahriansyah, 2019). When working, blades rotate at high speed driven by the motor. A particle diameter of 100−250 μm could be achieved at a speed of 4200 r/min (Luo et al., 2014). The stalks fed into the machine are then torn by the sharp blades. The combination effects of striking and cutting results in short fiber bundles and shives (Servili et al., 2002). The disadvantage of this technology is the impure outcome (fiber bundles) with much core. Blades need to be changed frequently to ensure crushing efficiency.

Compared with blade crushers, hammer mills are milder in fiber processing which achieve essentially a striking effect. A hammer mill (Munder et al., 2005) is composed of a chamber with a high speed rotor inside (Fig. 3). The rotor consists of a disk with walking hammers suspended on it. While working, the rotor rotates at high speed, making the hammers radial out due to centrifugal forces. The introduced stalks are then immediately crushed into pieces by the intensive tearing forces of hammers. Hammer-mill decortication has high extraction productivity, but it fails to produce high quality fiber of long or average length. A high yield of 96.4 % could be achieved with a fiber purity of 79.1 %, but the length of fiber varied from 20−100 mm (Thakur et al., 2017). The fiber purity is yet to be improved, whilst the energy consumption needs to be reduced (Sadek et al., 2011).

A roll crusher (Hulle et al., 2015) is composed of one or more pairs of rollers rotating towards each other (Fig. 4). When running, stalks fall down the upper feeding port of the equipment. The stalks are then brought into the designed gap between the rollers by the action of friction. The bark is able to pass between the rollers without being crushed whilst the shive is broken into short lengths. Often, at least one of the rollers has a blade or is fluted. The fiber bundles finally leak out of the lower part. Advantages of roll crushers include long fiber length and low energy consumption. But this method is only applicable for retted stalks.

Ball mills can also help to separate shives and fibers. During the hammer mill or the roll crusher decortication, fibers are easily wrapped into the clearance between the parts and heap up. This may lead to overheating and impeded running. Thus ball-mill decortication emerged in response to the problem. A ball mill (Fig. 5) is primarily composed of a feeding shaft and a horizontal barrel with moving grinder balls inside. The barrel starts to rotate as stalks are fed into the feeding shaft, driving grinder balls tumbling from the inertia and centrifugal force influences.

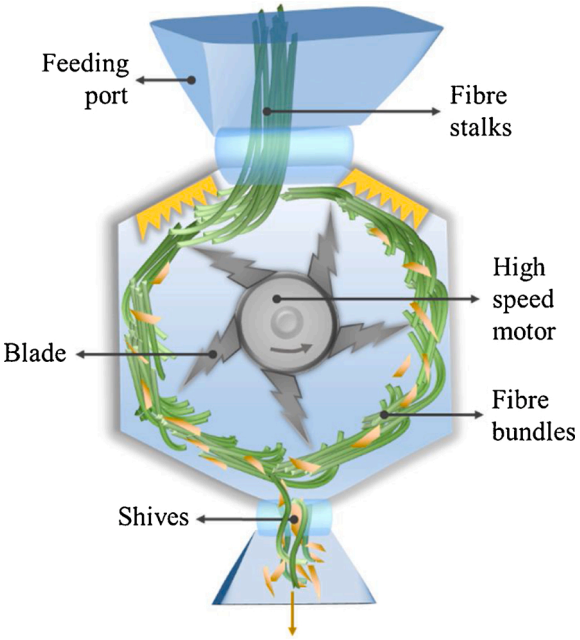

Fig. 2. The sketch of a blade crusher.

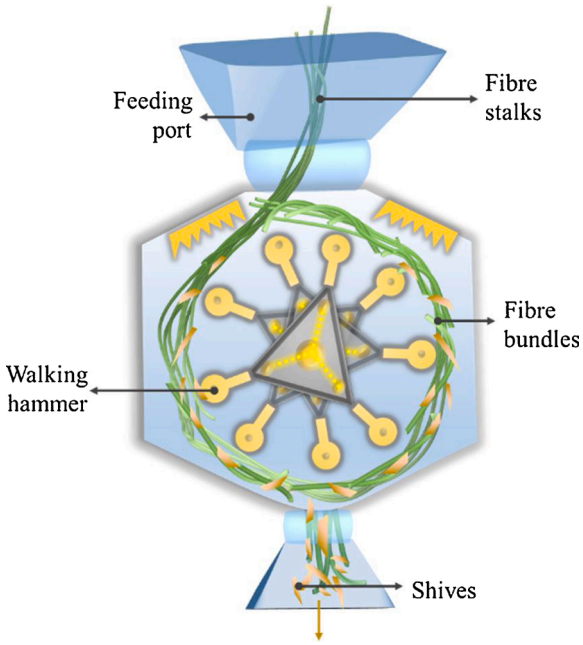

Fig. 3. The sketch of a hammer mill.

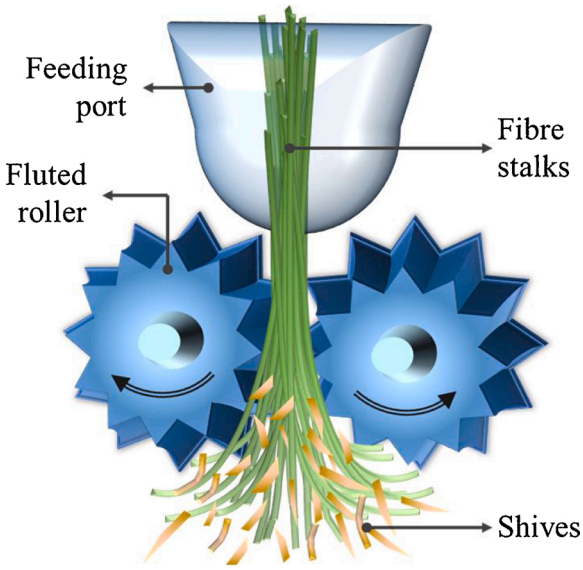

Fig. 4. The sketch of a roll crusher.

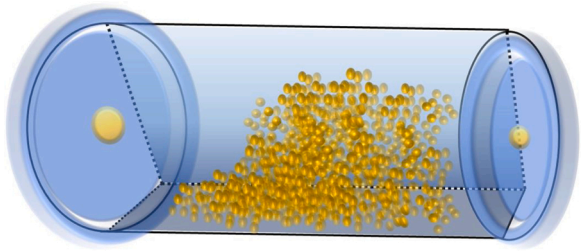

Fig. 5. The cross section of a ball mill.

The falling abrasives then break up stalks in the barrel causing fiber separation. A high core yield at 20.3 % could be achieved with a grinding speed of 250 rpm for 6 min duration (Baker et al., 2010). Even though ball mills can prevent fiber wrapping, fiber damage as well as fiber loss is still severe due to the process. And the discontinuous process may hinder large scale of production.

A planetary decorticator is an improvement on a blade crusher, a roll crusher or a ball mill (Liu et al., 2020; Slimani et al., 2018). Generally, it contains two or more pairs of beaters inside the chamber. An example of a planetary-roll crusher is depicted in Fig. 6. Beater pairs have different running speed, roughness and size. The variability is designed to keep fiber bundles intact and break shives into pieces through continuous crushing. Planetary decorticators can be used for both retted and unretted stems. From a planetary-roll crushing, hemp stalks were reported to have the same yield (at 30 % by mass) and fiber tenacity (at 0.38 N/tex) for both retted and unretted samples. Fiber impurities varied from 2−4 % (Hobson et al., 2001). Planetary decorticators have higher production efficiency compared with the single roll crusher or ball mill, but the quality of final fibers is yet to be improved. A planetary decorticator is applicable for both unretted stems and retted stems because all produced fibers could meet the market requirements while the cost of unretted fibers should be less.

Modified machines tend to be more effective in field decortication. The modified roller crusher, D8 Static Decorticator machine, developed by Adrian Clarke (Kovess, 2018) managed to extract the fiber from the hemp plants in a fraction of the time taken by other methods. This is because the invention operates in the field at the time of harvest whilst most decortication occurs in a factory. Another in-field decorticator is a modified forage harvester (Gratton and Chen, 2004). It has three knives and nine scutching bars, while a traditional harvester has 12 knives. Reduced knives contribute to less fiber being cut producing longer fiber; accessorial scutching bars increase shearing forces and improve fiber-core separation. Modified machines provide convenience and economic savings to the grower, as transportation of the shive to processing plants is not required. The improved machine can achieve a fiber yield at 61 % with a purity of 52 % which needs to be maximized. Whilst prototypes of infield decorticators have been shown to work few have been scaled up for industrial use.

3.1.2. *Fiber cleaning*

After decortication, stalks are changed into three types: fiber bundles, fiber-shive samples and shives. This is attributed to the incomplete loosening of fibers and shives. In the fiber cleaning stage, the partially adhered shives and impurities can be removed. Machines for fiber cleaning include scutchers, step cleaners and comb shakers.

Scutchers consist of feeding rollers and a tambour (Fig. 7), which is a disk with walking blades or pins. During scutching, the impure fibers are transferred to the tambour by feeding rollers. Shives are rubbed and crushed by the rotating tambour and together with dust, fall into the noil area due to gravity. Scutching is efficient as the feed quantity can reach 500 kg per meter of the working width, but the fiber loss varies from 5−50 % with different (one or two) pairs of rollers. Retted stems can achieve a fiber yield at 72 % whilst 48 % for incomplete retted stems, so it is not applicable for unretted samples (Akin et al., 2005).

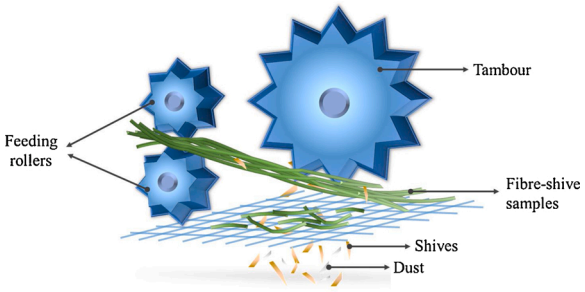

Fig. 7. The sketch of a scutcher.

Step cleaners (Fig. 8) consist of six or more rollers arranged similar to a flight of stairs. Rollers are designed with beaters around them. At the beginning, as the samples are fed into the process, the extensive hitting may loosen the cohesion between shives and fibers. The following impacts with the beater rollers smash the shives further and most fall through a mesh panel into the noil area. The continuous forces substantially increase the separation efficiency compared with scutching. A fiber fineness of 2.5−15 tex can be achieved with a fiber length from 50−200 mm (Munder et al., 2005). As step cleaners have several rollers with beaters, the energy consumption would be higher than one-roller

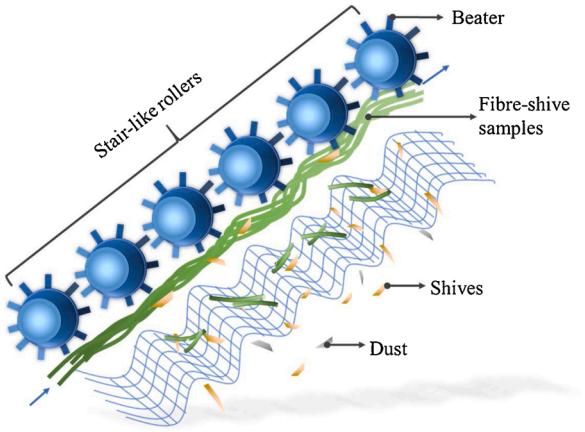

Fig. 8. The sketch of a step cleaner.

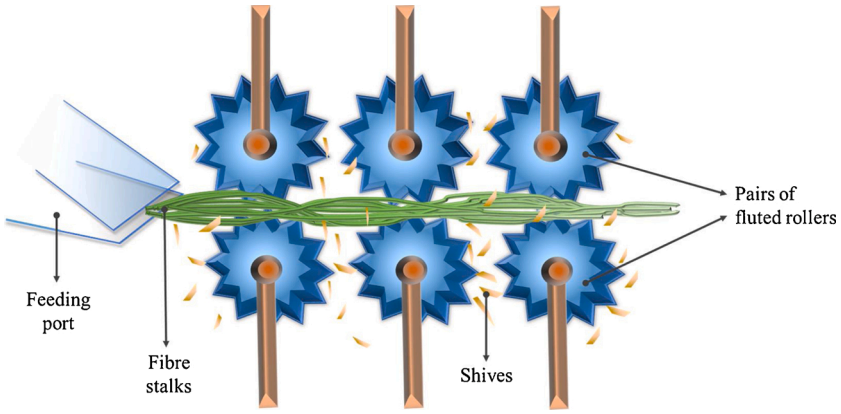

Fig. 6. The sketch of a planetary-roll crusher.

cleaners. It is applicable for large scale of treatment.

A comb shaker (Fig. 9) is made up of reciprocating pin gears arranged like a comb. Shives fall through the grid whilst the fiber layer, tiled on the floor grid, is combed. Compared with scutching and step-cleaning, combing is more moderate as it has a lower running speed. A fiber mixture with more 50 % of impurities can be combed and cleaned. It is applicable for producing high-level hemp or flax reinforced materials and short fiber cleaning (Pecenka and Fürll, 2008).

3.1.3. Fiber opening

Dust and shives are generally removed from fiber bundles after decortication and fiber cleaning. Fiber bundles, which are still stuck together by gums, are then subjected to fiber opening to produce fine or individual fibers for commercial use. The equipment used for fiber opening includes opening cylinders and carding machines. Since cotton ginning equipment has similar ginning rollers, it is also an efficient way of removing the trash.

Opening cylinders (Munder et al., 2005) (Fig. 10) are densely covered with sharp pin gears arranged in different needle gauges. The moving cylinders drive fiber bundles into combing, stretching and parallel. Fine fibers are sucked off pneumatically whilst big fiber bundles continue to be reprocessed. 650 kg of processing fibers can be fed in transferred by one meter working conveyor belt. The major disadvantage is that fine fibers between gears need to be cleaned out frequently to avoid fiber wrapping.

A carding machine (Fig. 11) consists of three parts: the pre-combing part (mainly consists of a licker-in roller and a feed roller), the primary combing part (mainly consists of a cylinder, a cover plate and a doffer) and the final-sample part (mainly consists of a pair of stripping roller and pressure roller). Fiber bundles are fed into the pre-combing process by the feed rollers and held by the licker-in roller while combing and sorting out short fibers. Shive will drop out between feed rollers and licker-in or between licker-in and cylinder. After initial carding, fibers are carried into primary combing, further rubbing between a big cylinder and a cover plate. The doffer helps to aggregate the carded fibers. In the final-sample part, free fibers on the doffer are collected and merged into the main group by the stripping rollers. Pressure rollers are responsible for packing the fibers into a well-knit layer which can be easily transported. Fibers can be fully loosened after the three-stage carding producing desired elemental fibers. A fiber tenacity of 19.7−25.5 cN/tex and a fiber elongation of 6.6−7.7 % can be achieved. However, the fiber uniformity is low with a uniformity index varying from 65−77 and fiber wrapping might be more serious in the opening cylinders processing (Göktepe et al., 2003). The tunable working speed makes it applicable for producing fibers with desired length.

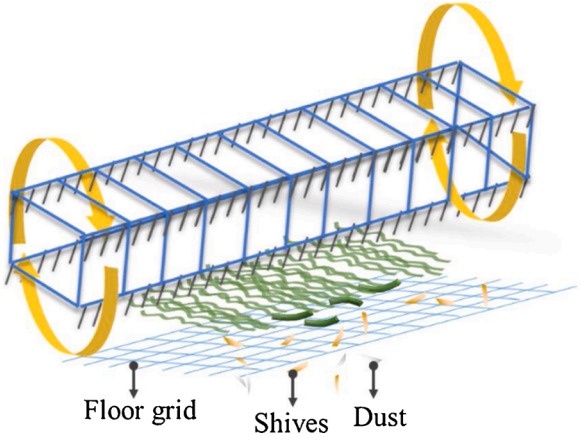

Fig. 9. The sketch of a comb shaker.

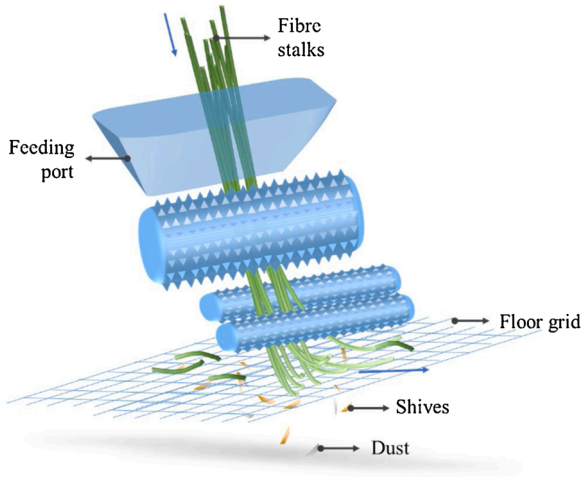

Fig. 10. The sketch of an opening cylinder.

3.2. Semi-physical methods

Semi-physical methods include two types of degumming: 1) the physical process needs further chemical or biological treatments; 2) physical interactions proceed in aqueous solution together with additive chemical reagents, enzymes or microorganisms. Semi-physical methods refer to steam explosion (type 1), microwave energy assistance (type 1 and 2), cryogenic treatment (type 1), ultrasonic treatments (type 2) and supercritical carbon dioxide treatments (type 2). A combined process is inevitably needed to achieve desired fiber properties.

3.2.1. Steam explosion

Steam explosion was initially proposed to produce cellulose nanowhiskers in 1927 (Deepa et al., 2011), and began to be applied in flax fiber extraction by R.W. Kessler et al. (Kessler et al., 1998) in 1998. At the time the process was viewed as a promising pre-treatment method which still needs successive chemical or biological treatment.

Steam explosion of bast fibers requires two major steps: heating by high pressure, saturated steam followed by steam expansion among the fiber matrix. Water-infiltrated fiber bundles are firstly fed into the chamber under high temperature (160 °C–260 °C) and pressurized atmosphere (0.69 MPa to 4.83 MPa) (Linde et al., 2008). Under the heat and high-pressure circumstance, hydrolysis of gums among the fiber bundles intensifies, which is further enhanced by the high moisture content of the stems. After a fixed time, the treatment vessel is opened while under full pressure instantly exposing the fibers to atmospheric pressure. This induces a rapid expansion of steam inside the fiber matrix that helps to separate the elemental fibers disrupting the recalcitrant cell wall structure (Behera et al., 2014). Zhang et al. (Zhang et al., 2019) proved that with the assistance of steam explosion, the hydrolyzation of hemicellulose and lignin content from raw kenaf increased 3.72 % and 6.25 % respectively compared with normal lye boiling. Another advantage is that steam explosion associated degumming process could reduce the entire chemical oxygen demand to 35 %, which may have an environmental processing benefit (Jiang et al., 2018).

The major shortcoming of steam explosion is the danger of operation. When the vessel pressure is released to atmospheric conditions, the steam expands resulting in a high burst of energy into the environment. This high energy environment is potential complicated to protect operators from the high temperature, noise and pressure of the release. The sudden drop in pressure may also cause rapid stress change in the pressure vessel resulting in reduced service life. Other disadvantages lie in incomplete disruption (Oliva et al., 2003).

3.2.2. Microwave energy assistance

Microwaves refer to electromagnetic waves with a frequency from

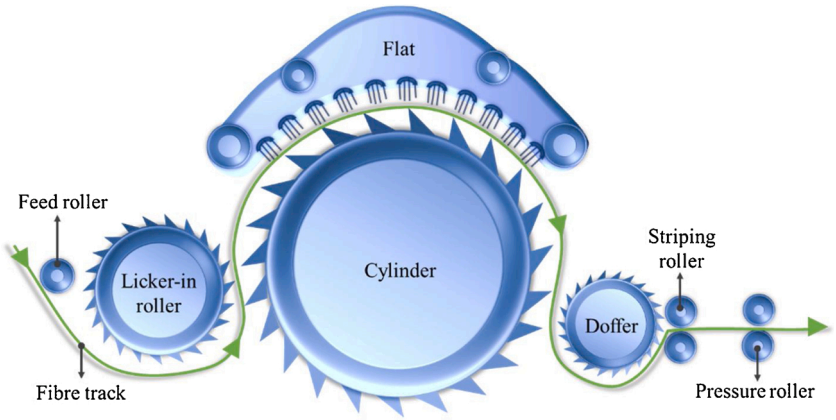

Fig. 11. The sketch of a carding machine.

300 MHz to 3000 GHz, which normally operates at a frequency of 2.54 GHz. It has a wavelength between 1 mm and 1 m (Motasemi and Afzal, 2013). It has had an important role in chemical reaction and organic synthesis since early 1980 (Balu et al., 2012; Polshettiwar and Varma, 2008). Assisted with further treatments, microwave energy is regarded as a good candidate for pre-treatment of lignocellulosic biomass.

In the process of microwave extraction, bast fibers need to be soaked in water to have moisture molecules within the gum structure before microwave heating. As a result, the moisture is uniformly distributed among cell walls in the stem. The moisture, as polar molecules with high dielectric loss, has strong absorption capacity for microwaves and converts microwave energy into heat. Cellulose and gums have a low dielectric loss and show less absorption response to microwaves (C. Li et al., 2020; Nair et al., 2016). During microwave heating, the water molecules can generate 2.450 billion vibrations per second due to the high microwave frequency and heat up immediately. The excited water molecules tend to cause separation or even fragmentation of surrounding cells which are connected by gums. After a fixed time, gums are more likely to be exposed and easily removed by further treatment. The extraction efficiency is primarily influenced by the moisture content, microwave energy and the microwave heating time. The moisture content is evaluated by the pre-soak time. 24 -h pre-soaking of flax stems at a 1:10 liquid-solid ratio shows the maximum retting efficiency of 100 %. Hemicellulose can be reduced to 6 % for 36 h treatment whilst a longer soaking of 48 h may lead to mechanical damage to single fibers (Raveendran Nair et al., 2013).

Microwave technology is a large user of electrical energy. This method of treatment could meet the requirements of sustainable development if the electrical energy was generated using renewable means as there are no chemicals involved other than water. If the equipment is not correctly designed or maintained some possibility of danger exists in operation, due to the exposure of workers to microwave radiation.

3.2.3. *Cryogenic treatment*

Cryogenic treatment uses the differences in thermal expansion within a material structure during cooling to low temperatures, to manipulate or change a materials' structure. Cryogenic treatment was first proposed by Gulyaev et al. (Gulyaev, 1937) in 1937. Later on, it began to attract attention from industrial technicians and academics for its excellent contribution in enhancing the performance of materials. Cryogenics has seen significant use in metal grain refinement and medical construction (Diekman and Papp, 2009; Sharma et al., 2008). There are four major parameters during cryogenic treatment: soaking temperature, soaking time, cooling rate and heating rate.

Cryogenic treatment for hemp degumming (J. Liu et al., 2018) utilised micro-cracking of the gums that hold the fibers together during the cooling and reheating cycles. A high cellulose content at 78.93 % can be achieved with by cryogenic treatment with a reduced hemicellulose and lignin content at 7.16 % and 2.82 %. The mechanism lies in the difference in the linear coefficient of thermal expansion between the fibers and gums (Bechel and Kim, 2004; Melcher and Johnson, 2007). During subzero treatment the rapidly changing temperature creates residual thermal stresses that create internal stresses that lead to the formation of micro delamination and cracking (He et al., 2013; Jang et al., 1987). Mechanical and or chemical processing of the cryogenically treated fibers needs to be conducted to complete the separation process. Cryogenic treatment can be expensive and is hard to scale which may limit the industrial application of this technology.

3.2.4. *Ultrasonic treatments*

Degumming with ultrasonic treatment tends to proceed in an aqueous solution with additive chemical reagents or bio-organisms.

Ultrasonic treatment utilizes a sound wave with a frequency higher than 20,000 Hz transferring in the form of mechanical vibrations (Bang and Suslick, 2010). When propagating in the water-fiber matrix, a large number of small bubbles can be generated due to the alternating appearance of positive and negative pressure. The bubbles rapidly grow before imploding with high temperature and pressure. This is called acoustic cavitation. The collapse of bubbles in a bulk liquid is different from bubble collapse beside a surface. (Borsa et al., 2016). When a bubble collapses next to a surface it sends a high-pressure jet of fluid at the surface. During the generation of the jet, chemicals can be transferred to the surface and help to dislodge surface materials such as gums and non-cellulosic materials (Syafri et al., 2019).

The corrosion by ultrasound of the fiber can be explained by the collapse of the air-filled bubble next to the fiber surface which causes a jet of the treatment liquor to be drawn through the bubble and impact the fiber surface. The implosion causes small localised high temperatures and pressures at the point of bubble collapse (Fig. 12) (Ben Hamida et al., 2017). The thickness of the liquid/surface boundary layer of a sample treated with ultrasonic agitation can be reduced to 1–8 % of untreated sample allowing treatment chemistry to access the surface (Hurren et al., 2008). Acoustic cavitation occurs at the interface of fibers and drives liquor to transfer. The movement will make it easier for chemicals to get to the gum and break it down. The existing chemical reagents or enzymes will further remove residual gums. The advantages of ultrasonic agitation include provision of access for reagents to penetrate into the fiber matrix and reduce the chemical dosage. The disadvantage is the limitation of ultrasonic wave penetration into a fiber mass. The fiber must be in a relatively large liquor ratio to enable penetration which increase water consumption and the volume of effluent produced.

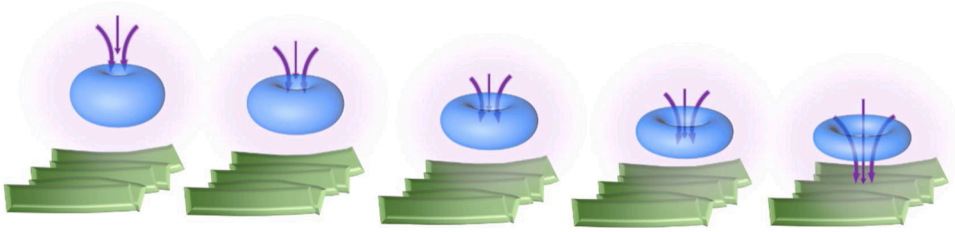

Fig. 12. Implosion of reagent-bubble under ultrasonic irradiation on the fiber layer.

3.2.5. Supercritical carbon dioxide treatments

Supercritical condition refers to the state where both the pressure and temperature of a fluid exceeds the critical pressure and critical temperature (Woods et al., 2004). Supercritical carbon dioxide (CO_2) has become the most common used supercritical fluid due to its low critical temperature and pressure, as it occurs commonly in the atmosphere and is nontoxic. Since CO_2 is a non-polar molecule, it can only extract lipids with lower polarity and low molecular weight (Jiménez-Carmona and Luque De Castro, 1998). Thus when extracting non-cellulose materials with high molecular weights, polar reagents are added into the supercritical fluid. In the degumming of flax fibers (Seghini et al., 2020), the infiltration of supercritical CO_2 causes fiber swelling or cell burst. The exposed gums can be removed successfully due to the extraction of the CO_2 combined with the additives such as pectinase, xylanase, laccase and disodium phosphate (Gao and Yu, 2018). A reduced tensile strength was observed from 236 ± 57 MPa (as-received yarn) to 211 ± 36 MPa (CO_2 treated yarn) caused by loosing of single fibers in a bundle-like yarn. Contamination of the treatment fluid is reduced significantly by evaporation of the CO_2 by a pressure change resulting in very small volumes of highly concentrated effluent after the process. The CO_2 can then be recompressed and reused while the effluent can be treated and rendered nontoxic. Gum extraction by supercritical CO_2 can help to swell the fiber and allow following chemicals to digest gums. The shortcomings are hardly obtained energy to compress the CO_2 and the cost of fabricating the qualified vessels that can work at the high pressures of supercritical CO_2.

3.3. Chemical treatment

Chemical degumming aims to dissolve the wastes from the individual fibers (Mazian et al., 2020). Even though chemical treatment may involve high oxygen demand, it is still a highly popular method because of the high efficiency and short treatment time. To get better fiber quality, during chemical treatment, reaction reagents need to be well controlled to avoid over or insufficient degumming.

3.3.1. Alkali treatment

Alkali treatment is a commonly used method for gum removal, normally with sodium hydroxide (NaOH) and auxiliaries (Fiore et al., 2015; Mahjoub et al., 2014; Xu et al., 2020). NaOH will react with the hydroxyl group in lignin phenol and form the phenolate as an intermediate and it finally converts to enol ether. Auxiliaries accelerate the hydrolysis. One of the most normal systems used by industry is the two-step alkali treatment (Cui et al., 2018). In the first step, the pre-treated bast fibers are subjected to 0.18 mol/L NaOH with 0.25 mol/L Na_2SiO_3 for 2 h at 100 °C. In the second step, fibers need boiling in 0.33 mol/L NaOH with 0.07 mol/L $Na_5P_3O_{10}$ for 2.5 h at 100 °C. Final fibers are obtained by further pickling, washing and drying. The obtained fibers had a residual gum content of 2.98 %, average fineness of 1532.03 Nm and breaking tenacity of 6.03 cN/dtex. Parameters can be altered for various expectations and different types of final fibers. Different alkali treatments with various combinations of chemicals are listed in Table 3. Variations mainly include the concentration of alkali solution, immersion duration, immersion temperature, the type of auxiliaries and the pre-treatment process. Multi-factor interactions exist in the experimental process (Hashim et al., 2017; H. Liu et al., 2013).

Alkali plays a major role in degumming as it can impose swelling to fiber cells and react with hydrogen bonds within fibers. The reaction primarily takes place in amorphous regions (consisting mainly of gums) and leaves most of the crystalline area (consisting mainly of cellulose

Table 3
Optimum parameters and obtained fiber quality (average value) in different alkali degumming methods.

Treated fiber	Pre-treatment	Main degumming	After degumming	Rinsing	Dry	Obtained fiber quality (average value)	Reference
Kenaf	–	6 % NaOH, 48 h, 25 ℃	–	Washed with distilled water	25 ℃ for 48 h, then 100 ℃ for 6 h	σ (Shape parameter) = 6.09. σ (mean value) = 519.52	(Fiore et al., 2015)
Kenaf	–	5 % NaOH, 1 h, 160 ℃	Neutralized (pH = 7) with CH3COOH	Washed with tap water	80 ℃ till dried	Length = 468 μm; diameter = 18.2 μm; aspect ratio = 16.0	(Shi et al., 2011)
Kenaf	Water retting	5 % NaOH, 24 h, 25℃	–	Immersed in distilled water, 24 h.	Hang to dry	Tensile strength = 625 MPa; tensile strain = 1.8 %	(Mahjoub et al., 2014)
Kenaf	Water retting	6 % NaOH, 4 h, 60 ℃	Neutralized (pH = 7) with CH3COOH	Washed with tap water	100 ℃, 1 h	Diameter = 80.05 μm; weight loss = 20 %; fiber density = 1.275 g/cm^3	(Hashim et al., 2017)
Hemp	1 % H_2SO_4, 2 h, 50 ℃	2 % NaOH, 5 % Na_3PO_4, 3 % Na_2SO_4, 2 h, 80 ℃	–	Washed with distilled water	80 ℃ till dried	Tensile strength = 5 cN/tex; diameter = 19.32 μm	(H. Liu et al., 2013)
Hemp	5 % NaOH, 2 h, 30.5 ℃	5 % NaOH, 2 % Na_2SO_3, 2 h, 120 ℃	–	Washed with distilled water	80 ℃, 48 h	Fiber diameter = 22.38 μm; tensile strength = 833 MPa	(Sunny et al., 2020)
Hemp	–	5 % NaOH, 2 % Na_2SO_3, 1 h, 120 ℃	–	Machine washing, 45 min	70 ℃, 48 h	Fiber diameter = 25.9 μm	(Islam et al., 2011)
Alfa stem	–	5 % NaOH, 1 h, 120 ℃	0.7 % NaClO, 2 h	Washed with distilled water	60 ℃, 48 h	Fiber length = 540 μm; diameter = 26 μm; aspect ratio = 21	(Borchani et al., 2015)

* Fractions are reported as wt % based on the amount of the total solution.

materials) unaffected (Ramasamy et al., 2018). Fibers are assisted to separate from each other in the degumming system while alkali devotes to gum removal. Gums are further split into smaller elemental units and dispersed in the treatment liquid allowing the fibers to remain intact. An increase of alkali concentration may cause damage to the fiber texture producing fine and brittle fiber quality. The immersion duration mainly influences the tensile property of bast fibers. A longer treatment time will lead to the decrease of tensile stress and Young's modulus (Fiore et al., 2015). The high immersion temperature results in short fiber length. Kenaf bast fibers immersed in the alkali solution at 160 ℃ can reach 0.05 to 0.87 mm in length which may not need further opening (Shi et al., 2011).

Auxiliaries act as assistants to the alkali, helping to achieve wetting or to hold broken-down gum and other contaminants in suspension. Commonly used additives include trisodium phosphate (Na_3PO_4), sodium tripolyphosphate ($Na_5P_3O_{10}$), sodium sulphite (Na_2SO_3), sodium carbonate (Na_2CO_3), sodium bicarbonate ($NaHCO_3$), sodium silicate (Na_2SiO_3), sodium hypochlorite (NaClO), acetic acid (CH_3COOH) and surfactants, etc. Na_3PO_4 and $Na_5P_3O_{10}$ are chelating agents which may have emulsifying and penetrating effects in the alkaline solution. The strong dispersing ability can produce complexation of multivalent ions such as magnesium and calcium ions. The complexation can lead to the dispersion of gums which have peeled off but not dissolved in the solution. Thus, the dissociative gums will no longer re-adsorb on the surface of bast fibers. Na_2SO_3, Na_2CO_3, $NaHCO_3$ and Na_2SiO_3 serve as supplements of the alkali source for the generation of hydroxyl ions during the hydrolysis. In alkali degumming, NaOH is gradually consumed. The supplementary hydroxyl ions ensure the continuous decomposition of non-cellulose materials. NaClO is a strong oxidant which can help degrade residual lignin in alkali degumming. CH_3COOH normally acts as a neutralizing reagent in the later period of alkali degumming. Surfactants and detergents are used to enable effective wetting of the fiber and help to stop dissolved extracted materials redepositing onto the fiber surface.

Pre-treatments (L. Wang et al., 2007) aim to remove a small amount of gum by wetting or swelling the raw fibers, it also helps open up the pathways of chemical into the composite structure by swelling and starting to crack the fiber to fiber interface. The process also facilitates the infiltration of the following reagents and improves the removal effect. Anyone of the four major types of degumming methods can be regarded as a pre-treatment process. Practical degumming is attributed to the combination of two or more methods.

Alkali degumming is more effective than physical treatments, but it may produce inhibitors during reactions which involve the combination of two or more chemicals.

3.3.2. Oxidation

Oxidative degumming is a potential alternative for alkali treatment to avoid refractory by-products (Teong et al., 2019). Oxidants used in degumming include sodium percarbonate ($2Na_2CO_3{\cdot}3H_2O_2$) and hydrogen peroxide (H_2O_2). $2Na_2CO_3{\cdot}3H_2O_2$ is an unstable complex formed by sodium carbonate, H_2O_2 and water. It is a strong bleaching and oxidizing reagent. H_2O_2 has an oxygen content up to 47.1 wt % and can generate active hydroxyl radicals (Yi et al., 2016). It is a green oxidant as water and oxygen are the only decomposition products. In oxidation degumming, gum is almost always easier to depolymerize than cellulose because of the low degree of polymerization. So the fiber extraction can be completed within an hour with 0.15 mol/L H_2O_2 (Zhaoling Li et al., 2016;Li and Yu, 2015). The main parameters include the concentration of oxidant, treatment duration and reaction temperature. It is vitally important to stabilise the concentration as the oxidation ability is strong and may lead to intensive reactions. For example, the excess amount of H_2O_2 may result in cellulose damage and environment pollution (Barbosa et al., 2013), which can be detected by the value of chemical oxygen demand (COD). Whilst insufficient amount of hydroxyl radicals would result in gum residues in final fibers. Based on this, oxidizing stabilizers are added to maintain the content of hydroxyl radicals.

Oxidizing stabilisers consist of NaOH, $NaSiO_3$, tetra sodium pyrophosphate ($Na_4P_2O_7$), $Na_5P_3O_{10}$, magnesium dihydroxide ($Mg(OH)_2$), magnesium sulphate ($MgSO_4$), sodium sulphate (Na_2SO_4), urea (CH_4N_2O), and Fenton solution (consist of hydrogen peroxide and ferrous salt) etc. (Li et al., 2016;Li and Yu, 2015;Meng et al., 2019;Meng et al., 2016; Teong et al., 2019;Zhang et al., 2019). Different combinations of oxidative degumming are listed in Table 4. It is reported that the decomposition speed of hydrogen peroxide can be controlled by pH value. The pH values and solubilities of catalysts are different. Thus, the combination of two or three catalysts with a large difference in pH or solubility can control the total pH in the reaction. For degumming a pH value higher than 10 may catalyse the oxidising reaction and promote gum extraction (Kim et al., 2000; Saito et al., 2009).

NaOH acts as a provider of the alkaline environment to ensure the oxidising activity. $NaSiO_3$, Na_4P_2O, $Na_5P_3O_{10}$, $Mg(OH)_2$, $MgSO_4$ and Na_2SO_4 serve as buffering agents as they can generate hydroxyl ions at a lower speed than NaOH. Urea can be hydrolysed into ammonia which presents alkaline properties and supplements the consumed alkali in the reaction. Fenton involves reactions of peroxides with ions to form active oxygen species that oxidize organic or inorganic compounds. It is a practical treatment which can be applied at room temperature and atmospheric pressure. The function of ferrous ion is to catalyse hydrogen peroxide to produce hydroxyl radical for lignin removing (Hu and Ragauskas, 2012; Kato et al., 2014).

The advantage of oxidative degumming is that it takes less time than alkali degumming, but the strong oxidising ability may lead to partial degradation of the cellulose fibers.

3.3.3. Organic solvents treatment

The application of organic solvents in degumming derives from the contribution in biomass isolation for paper pulping (Paszner, 1985). The reaction takes place in a water matrix with both organic solvents and catalysts. Catalysts mainly consist of salts and acids, such as sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium sulfate ($MgSO_4$), ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2(SO_4)_3$), cupric chloride ($CuCl_2$), aluminium chloride ($AlCl_3$), acetic acid (CH_3COOH), formic acid (HCOOH) and sulphuric acid (H_2SO_4), etc. (Agnihotri et al., 2015; Hideno et al., 2013; Nitsos et al., 2018; Pan et al., 2007; Paszner and Behera, 1989; Y. Qu, Z. Qin, et al., 2020). In a high temperature and high-pressure atmosphere, organic solvents can penetrate into the intervals between single fibers where gums inhabit. The solvent molecules further split aryl ether bonds and ether bonds in lignin or between lignin and triggered carbohydrates. Then catalysts accelerate the dissolution speed of decomposed and residual gums into the solution (Qu et al., 2021; Y. Qu, S. Zhao, et al., 2020). Fine fibers are obtained after rinsing and the remaining solution can be distilled and reused.

In the early stages, organic solvents used for gum removal include methanol (CH_3OH) and ethanol (C_2H_5OH) (Bozell et al., 2011). But the resulting high pressure increased safety risks because of solvent high volatility and flammability. Then arose the ester solvents, organic bases, ketones, and high boiling solvents including glycerol ($C_3H_8O_3$), glycol ($C_2H_6O_2$), propylene glycol ($C_3H_8O_2$), 1,4-butanediol ($C_4H_{10}O_2$), and butanol ($C_4H_{10}O$), etc. (Jiménez et al., 1999; Johansson et al., 1987; Qu et al., 2020a, 2020b, 2020c). Ramie fibers degummed using a glycol solution showed the highest fiber yield with only 3.28 % of residual gum content (Y. Qu, S. Zhao, et al., 2020). Different combinations of organic solvents and catalysts for degumming are listed in Table 5.

Another kind of organic solvent, deep eutectic solvent (DES), has emerged for fiber extraction in recent years. Two or three well-associated chemicals from hydrogen bond donors (urea, renewable carboxylic acids or renewable polyols) and hydrogen bond acceptors (choline chloride, betaine, etc.) can easily mix DES. (Huang et al., 2021). The most distinct property of DES is its lower melting point as compared to the original components. As a substitution of ionic liquids (ILs), DES

Table 4
Optimum parameters and obtained fiber quality (average value) in different oxidative degumming.

Treated fiber	Pre-treatment	Main degumming	After degumming	Rinsing	Dry	Obtained fiber quality (average value)	Reference
Ramie	Steam explosion, 0.5 MPa, 5 min.	2 % $2Na_2CO_3{\cdot}3H_2O_2$, 3 % H_2O_2, 3 % $NaSiO_3$, 2 % $Na_5P_3O_{10}$, 2.5 h, 90 ℃	–	Washed with distilled water	80 ℃ till dried	Fiber fineness = 6.25 tex; breaking tenacity = 5.4 cN/tex	(Jiang et al., 2018)
Ramie	–	8 % $2Na_2CO_3{\cdot}3H_2O_2$, 2 % $Na_5P_3O_{10}$, 2 % CH_4N_2O, 2 % $MgSO_4$, 2 % Na_2SO_4, 2 % $NaSiO_3$, 2.5 h, 80 ℃	–	Washed till neutralized	85 ℃ till dried	Fiber fineness = 1440 nm; tenacity = 54.5 cN/tex; breaking elongation = 3.15 %	(G. Liu et al., 2011)
Kenaf	Steam explosion, 1.0 MPa, 2 min.	1% $FeSO_4{\cdot}7H_2O$, 3 % H_2O_2, 1 h, 100 ℃	1 % NaOH, 1 h, 100 ℃	Washed with distilled water	80 ℃ till dried	Fiber length = 48 mm; fiber fineness = 75 dtex; breaking tenacity = 3.24 cN/dtex	(Y. Zhang et al., 2019)
Ramie	–	6 % H2O2, 8 % NaOH, 2 %$Mg(OH)_2$, 4 % Na5P3O10, 1% $C_{14}H_8O_2$, 1 h, 85 ℃, then 1 h, 125 ℃	4 % $NaHSO_3$, 1 h, 90 ℃;	Washed with distilled water	90 ℃ till dried	Linear density = 5.6 dtex; fiber tenacity = 10.2 cN/dtex; elongation = 2.78 %	(Chaoran Meng et al., 2016)
Ramie	–	5 % H2O2, 5 % NaOH, 1 h, 85 ℃;	–	Washed with distilled water	3 h, 100 ℃	Linear density = 5.61 dtex; fiber tenacity = 6.18 cN/dtex	(Z. Li and Yu, 2015)

*Fractions are reported as wt% based on the amount of the total solution.

Table 5
Optimum parameters and obtained fiber quality (average value) in different organic degumming.

Treated fiber	Pre-treatment	Main degumming	After degumming	Rinsing	Dry	Obtained fiber quality (average value)	Reference
Ramie	–	1 % FeCl3, 99 % $C_3H_8O_3$, 2 h, 200 ℃	–	Washed with distilled water	3 h, 105 ℃	Fiber tenacity = 7.9 cN/dtex; fiber yield = 75.2 %; residual gum content = 3.88 %	(Y. Qu, Z. Qin, et al., 2020)
Ramie	Nitrogen purification, 0.4 MPa	100 % $C_2H_6O_2$, 45 min for 20−180 ℃; 15 min for 180−200 ℃; 60 min for 200 ℃	–	Washed with tap water, 10 min	2 h, 105 ℃	Fiber tenacity = 8.27 cN/dtex; linear density = 7.2 dtex; residual gum content = 3.28 %	(Y. Qu, S. Zhao, et al., 2020)
Ramie	Water boiling, 1 h, 100 ℃	50 % $C_2H_6O_2$, 50 % CH_3COOH, 15 min for 25−130 ℃; 6 h for 130 ℃;	–	Washed with tap water, 10 min	2 h, 105 ℃	Fiber tenacity = 6.53 cN/dtex; linear density = 6.58 dtex	(Qu et al., 2020a, 2020b, 2020c)
Ramie	Steam explosion, 0.5 MPa, 5 min.	choline chloride, urea, 2 h, 100 ℃	–	Washed with distilled water	90 ℃ till dried	Fiber fineness = 1419.99 Nm; breaking tenacity = 5.98 cN/dtex; residual gum content = 4.68 %	(Song et al., 2019a, 2019b)
Ramie	–	choline chloride, urea, 2 h, 100 ℃	Ball-milling, 3 h, 9000 rmp	Washed and filtered	60 ℃ till dried	Cellulose content = 88.6 %;	(Yu et al., 2019)

* Fractions are reported as wt% based on the amount of the total solution.

have many advantages such as easy to prepare, biocompatible and low ecological footprint.

Nano-fibrillation was achieved from birch cellulose pulp using the DES choline chloride-urea by a non-hydrolytic pre-treatment (Sirviö et al., 2015). This system and solvent was also used for the fibrillation of ramie (Yu et al., 2019). DES has been observed to have an effect on the fiber to fiber binding in bast fibers. Degumming using these solvents was done on apocynum venetum in a two-step process using a combination of DES and alkali (Song et al., 2019a, 2019b).

Degumming with organic solvents may have advocated potential for gum recovery due to the solubility differences of gums in various organic solvents. But handling of harsh organic solvents may be a problem.

3.4. Biological treatment

Enzymes and fungi derived from natural conditions (such as dew retting) or artificially added in an environment conducive to their use are mainly used in biological degumming. Natural degumming refers to dew retting and water retting, whilst artificial degumming is defined as controlled treatment of fibers with commercial enzymes or cultivated microorganisms.

3.4.1. Natural retting

Natural retting depends on the existing microorganisms in a field to achieve the fermentation of fiber bundles. With the joint corrosion and dissolving effect of bacteria and water on plants, fiber bundles are gradually separated from the stems (M. Liu et al., 2017).

Dew retting (Djemiel et al., 2017; Jankauskiene and Gruzdeviene, 2013) is adopted mainly in lands with heavy dew at night and high temperatures in the day. During dew retting, the harvested stalks are spread on the ground and fermentation by bacteria, sunlight, air, rain and dew to dissolve the non-cellulose materials in fiber intervals. The process lasts for 14–21 days.

In natural water retting (Dey et al., 2021; Di Candilo et al., 2010), fiber stalks or pealed fiber bundles are tied and pressed under stones or wood in a natural water tank, usually in a pool or river. Immersion for a long period contributes to the penetration of water into the fiber matrix. The internal fiber cells begin to swell and finally burst. A weight loss of 13.8 % can be achieved after 10 days of water retting. This exposes the gums which are gradually dissolved by microorganisms. After 8–14 days, retted fibers can be collected from the water.

Both of these two natural degumming methods meet the requirements of environmental and economic consideration. Water retted fibers even conceive higher colour brightness and better fiber quality than dew retted fibers. This may have resulted from the degumming-inconsistency in the exchange from day to night. The drawback of natural retting is that they are dependent on weather and land-possession, resulting in insufficient or over degumming and they prevent other crops from being sewn (Guo et al., 2020). Water retting is very effective in removing gums however these then contaminate the downstream watercourse often resulting in damage to aquatic organisms. As a result, the water retting source is replaced by artificial retting tanks in a

particular environment, which can be controlled to proper conditions benefiting degumming. The controllable parameters include environment and water temperature, air humidity, sun exposure, and retting time. Even mineral nutrition, ferments, and fluid recirculation are applied in the tank to accelerate the speed of decomposition (Konczewicz et al., 2013). Care needs to be taken to control the treatment and disposal of the water removed from the tanks and this process is still land and water intensive as treatment takes several weeks and often the water is changed multiple times during the retting process.

3.4.2. Extracted-enzyme retting

The process of extracted enzyme retting is to degum fibers in crude enzymes or in the diluent of purified enzymes. Crude enzyme solution can be obtained from filtering or centrifuging aging bacteria strains. Further purification, concentration or desiccation of crude enzyme solution results in high purity enzyme solution or powdery enzymes. According to the chemical composition of bast fibers, the primary enzymes required for degumming include hemicellulose, pectinase and ligninase (Jan et al., 2021).

Hemicellulase mainly refers to xylanase and mannanase. The mechanism lies in the decomposition of the β-1, 4 bonds in xylan chains. The broken bonds then partially release the connection between single fibers (Michael George et al., 2014). Pectinases are responsible for hydrolysing pectin resulting in the separation of gums and fibers (Akin et al., 2004;Zhang et al., 2000). Since few organisms can generate corresponding enzymes to degrade lignin, usable ligninase directly is rare in spite of laccase, manganese peroxidases and lignin peroxidase. Under the influence of the enzymes, the bonds between structural units break and the original high molecular weight compounds are decomposed into low molecular weight substances.

Enzymes own the characteristic of high specificity; thus a mixture of different enzymes is widely adopted in enzyme degumming. During the reaction, the enzymatic activity is mainly influenced by concentration, time duration, temperature, pH value and the presence of catalysts etc. The combination of laccase and hemicellulose in the TEMPO system is reported to remove 85 % of lignin and 58 % of hemicellulose at 50 °C with the pH value of 5 (Yeping et al., 2019). Extracted enzyme retting has the advantage of high efficient and low pollution, but the formation of the purified enzymes is a complicated process.

3.4.3. Cultivated-microorganism retting

A continuous production of enzyme is achieved by adding specified bacteria or fungi in the degumming system. The microorganism is cultivated and breeds in the matrix while generating enzymes and fulfilling the mission of degrading gums. Commonly used fungi and bacteria include *Pseudomonas*, *Enterococcus sp.*, *Bacillus subtilis*, *Bacillus sp. Y1*, *Bacillus cereus*, *Pseudomonas alcaligenes*, *Bacillus cereus*, *Brown rot fungus*, *White rot fungus*, *Streptomyces*, *Basidiomycetes*, *Ascomycetes*, *Rhizomucor pusillus*, *Streptomyces sp. S27*, *Paenibacillus campinasensis*, and *Geobacillus thermoglucosidasius* etc. (Benimeli et al., 2007; Cheng et al., 2018; F. Guo et al., 2013; Zeng et al., 2007). More than two types of microorganisms are added when degumming. Extra auxiliaries may also be needed to help with enzyme generation. A newly developed microbial consortium, RAMCD407, was found to extract ramie fibers with only 2.84 % residual gum content in 56 h (Mao et al., 2019).

Some of the existing strains may have a long degumming duration with still insufficient gum removal. Herein, chemical mutagenesis, gene clone, cell fusion and other technologies have been applied to microorganisms to improve the ability of enzyme production (Y. Wang et al., 2017; Yang et al., 2019; Zhou et al., 2017a, 2017b). The enzymatic activity as well as enzyme stability may also be strengthened. The recombinant xylanase was reported to have strong hydrolysis capacity to ramie hemicellulose. The new enzyme was cloned from the strain DCE-01, the enzymatic activity was enhanced by adding Cu^{2+}, Ca^{2+}, Mg^{2+}, and K^{+} (R. Wang et al., 2019).

Screened strains are highly effective in degradation of the non-cellulose materials, but the difficulties in cultivation and recombinant technologies make it a barrier in industry application.

4. Outlook

Present mini review work explored the processing required for the production of bast fibers from fiber stalks. It also highlighted the advantages and disadvantages of various processing techniques summarized in Table 6. Remedies for enhancing the degumming efficiency of the methods were mentioned in relevant paragraphs.

In spite of the diversity of degumming methods, there are still restrictions in the degumming industry. The major constraint is the lack of a simple and efficient technology that produces high-quality fibers with high yield. The combination of current technologies may enable the production of desired final fibers but cannot meet with the time-saving requirement. The second limitation is the inconsistency of final fibers in terms of their length and fineness. The products in different qualities may lower the real value of the long and fine fibers mixed in the group, which are supposed to be the best candidates in textile applications. The third restriction is the use of noil produced in mechanical degumming and fiber sorting. These fibers are short strands or tangled with knots. In factory, noil is reused on the rotor spinning machine. But this would influence the quality of yarns. Achieving high added value of noil is still a challenge. The fourth restriction is gum recovery after the chemical degumming process. Most existing methods ignore the recycling of the gum in residues, which is a waste of resources. The liquor after-treatment is normally neutralized and disposed of. There is potential for recovery of a lignin based product that could be used for other applications.

To overcome the potential hurdles mapped above, the first future work is to focus on creating modified degumming machines hopefully containing a chemical or biological treatment chamber before or after the mechanical extraction. The two-in-one design of the machine is very important since this will save the time required for transferring samples from one to the other degumming method. Mechanized production instead of manual can shorten the production time. Based on this, the operability as well as the safety of the designed machine should be considered for workers. It might be more acceptable if the machine could run in the normal ambient condition rather than under high temperature and pressure.

The second future work is to focus on the automatic classification of final fibers. On the one hand, a fiber sorting machine can be designed for fiber finishing use. At present, degummed fibers are manually classified into several grades according to GB/T 18146.1−2000. Fibers in different grades are preferable in different fields. For example, hemp fibers with low yellowness, small diameter and high luster are listed as first-class products. These fibers are largely used for textile production. Low grade samples can be made into composites with polymers. On the other hand, raw materials with different lignin content should be treated with different methods or method combination. This is because different raw material may have different lignin content which is divided into three levels: high lignin content ($\geq$ 5%), medium lignin content (3–5 %) and low lignin content ($<$ 3%). With an automatic classification machine, fiber evaluation will be objective and effective. This will help with accurate use of fibers in different grades.

The average production of noil from a hemp factory is 30 ton/month which equates to 13 % of all hemp processed for the month. Proper reuse of the great amount of noil can make huge benefit. The reuse of bast fiber noil can be learnt from cotton since they all belong to cellulosic plant fibers. These cellulosic fibers can be dissolved. On the one hand, the dissolved hemp can for aerogels. After hydrophobic treatment, the cellulose aerogels will change into a selectively oil-absorbing material capable of floating on water. The modified cellulose aerogels will be able to clean oil spills under a marine environment, while removing the oil spills is still a great challenge. On the other hand, the dissolved hemp can be used in wet spinning. During wet spinning process, polymers can be

Table 6
Major advantages and disadvantages of various processing techniques.

Methods		Advantages		Disadvantages	Reference
Physical extraction	Decortication	Manual operation	Easy operation.	Inefficient	(M. George et al., 2016)
		Blade crushers	Enable short length of fiber bundles and shives.	The outcome (fiber bundles) is impure with much core.	(Servili et al., 2002)
		Hammer mills	Have high extraction productivity and are more protective to fiber bundles compared with blade crushers.	Has high energy consumption and low production efficiency.	(Sadek et al., 2011)
		Roll crushers	Enable long fiber length with low energy consumption.	The method is only applicable for retted stalks.	(Hulle et al., 2015)
		Ball mills	Can avoid fiber wrapping.	Severe fiber loss in the process.	(Baker et al., 2010)
		Planetary decorticators	Have high production efficiency.	The quality of final fibers are yet to be improved.	(Hobson et al., 2001)
		Modified machines	More effective in field decortication.	The design of a modified machine takes time.	(Gratton and Chen, 2004)
	Fiber cleaning	Scutchers	High-feeding quantity up to 500 kg.	Not applicable for unretted samples.	(Akin et al., 2005)
		Step cleaners	Has higher separation efficiency comparing with scutching.	Has high energy consumption.	(Munder et al., 2005)
		Comb shakers	Moderate-processing could ensure long fiber length.	Low processing speed.	(Pecenka and Fürll, 2008)
	Fiber opening	Opening cylinders	High-feeding quantity.	May form fiber wrapping if fine fibers from between gears are not cleared frequently.	(Munder et al., 2005)
		Carding machines	Fibers can be fully opened.	Much easier to form fiber wrapping compared with opening cylinders.	(Göktepe et al., 2003)
Semi-physical methods	Steam explosion	Increase the hydrolyzation of hemicellulose and lignin content and reduce the entire chemical oxygen demand.		Dangerous process to undertake.	(Jiang et al., 2018)
	Microwave energy assistance	Gums exposed to large microwave energy.		May have potential harm to workers due to microwave radiation.	(Raveendran Nair et al., 2013)
	Cryogenic treatment	Form micro-cracking of the gums.		Can be expensive and is hard to scale.	(J. Liu et al., 2018)
	Ultrasonic treatments	Provide access for reagents to penetrate into the fiber matrix with low chemical dosage.		Has a limitation of treatment quantity.	(Syafri et al., 2019)
	Supercritical carbon dioxide treatments	Can swell the fibers and allow chemicals to digest gums.		Energy consumption for CO_2 compressing; high cost for the qualified working vessels.	(Seghini et al., 2020)
Chemical treatment	Alkali treatment	More effective than physical treatments.		May produce inhibitors.	(Hashim et al., 2017)
	Oxidation	Less time required than alkali degumming.		The strong oxidising ability may lead to partial degradation of cellulose fibers.	(Chaoran Meng et al., 2016)
	Organic solvents treatment	Have advocated potential for gum recovery.		Hard to handle/extract the residual organic solvents.	(Y. Qu, S. Zhao, et al., 2020)
Biological treatment	Natural retting	Meets the requirements of environmental and economic consideration.		These methods are constrained by weather-dependence and land-possession.	(Shekhar Sharma et al., 1989)
	Extracted-enzyme retting	Has high efficiency and low pollution.		Enzymes are difficult and expensive to produce in volume.	(Jan et al., 2021)
	Cultivated-microorganism retting	Screened strains are highly effective in degradation of the non-cellulose materials.		Difficult to cultivate and recombine technologies.	(Mao et al., 2019)

added can form composite fibers. In this case, the noil can be reconstructed and devote to another field more than textile.

The fourth future work is to focus on the recover and reuse of gum from degumming effluents. Degumming of bast fiber is similar to wood treatment for pulping, which all aims to remove the gum materials. The black liquor after pulping is always collected and purified to extract hemicellulose or lignin. These gum materials have great potential application in biology, reinforcing materials and medical science. Besides, monosaccharides are hydrolysed in the waste solution and should be considered before discarding as these materials are potential alternatives for the production of fermentable sugars.

There is still a large scope for the research of bast fiber degumming. Every effort should be made to augment research strategies to promote the production of elemental bast fibers with both high quality and high productivity as well as bio-refining of waste residues.

5. Conclusion

The mini review addresses the structure and degumming methods of bast fibers. Crucial points are listed below.

- A complete bast fiber plant is composed of bark, fiber bundles, and shives. Fiber bundles are composed of single fibers surrounded by the gum.
- The chemical composition of bast fibers includes cellulose, hemicellulose, lignin, pectin and wax. Cellulose has positive influence on the mechanical properties. Non-cellulose materials (gum) include hemicellulose, lignin, pectin and wax that work together to transfer nutrition and help to resist outside attack of the fiber.
- There are four categories of degumming methods: physical extraction, semi-physical method, chemical treatment and biological method. Practically, a combination of two or three methods will be applied to achieve acceptable fiber qualities.
- Physical separation of fiber bundles and shives purely depends on shearing, pressing or tearing forces. It is time-saving but with irregular sample qualities.
- Semi-physical methods involve chemical or biological treatments during or after the physical treatment. These methods may enable high fiber quality but with hidden danger of operation or lack of practicality.
- Chemical treatments are widely used for high efficiency and short treatment time. The chemical selection and the handling of waste

solution may be the biggest challenge due to environmental consideration.

- Biological treatments involve enzymes and fungi derived from natural conditions or artificially. The major advantage is the low environmental impact of effluents. The large-scale formation of effective enzymes and microorganisms is both expensive and difficult.
- Future work may focus on promoting the production of elemental bast fibers with both high quality and high productivity as well as the bio-refining of waste residues. Such as utilizing environmental-friendly chemical treatment associating with physical or biological treatment to achieve high efficiency and high fiber quality.

CRediT authorship contribution statement

Pei Lyu: Writing - original draft. **Yu Zhang:** Data curation. **Xungai Wang:** Project administration, Supervision, Writing - review & editing. **Christopher Hurren:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.indcrop.2021.114158.

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