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Review

Pulp and paper production from oil palm empty fruit bunches: A current direction in Malaysia

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Abstract

The pulp and paper industry is advanced rapidly since there are many types of raw materials containing cellulose fibres that could be used to produce different kinds of paper by different methods in the mills. In Malaysia, one of the abundant non-wood materials for pulp and paper production is empty fruit bunch (EFB) from the oil palm. The EFB is the main fibrous residue and natural fibre which has promising potential as an alternative to replace woody materials. This study provides insight into the use of EFB as an alternative non-wood fibre resource in pulp and paper making. The potential of oil palm EFB transformed into valuable fibre material was elaborated. In this review, detailed information on the properties of EFB for pulp and paper making process to identify the chemical composition and fibre morphology were discussed. Recent advanced applications including nanocellulose from EFB, polymeric hydrogel, and antimicrobial papers were discussed to demonstrate high commercialization for pulp and paper technology. The three-dimensional (3D) printing technique has been employed due to the high complexity of paper products. The future trends and challenges regarding the use of EFB in pulp and paper making were also reviewed. This study demonstrated that the EFB has met the demand of the market chains as a potential raw material in paper making and manufacturing.

1. Introduction

Malaysia generates a large amount of biomass along with the production process, in the form of EFB, palm oil mill effluent (POME) and palm kernel shell (PKE) (Aljuboori, 2013). The oil palm waste is proving to be an effective alternative to reduce production costs in the palm oil industry by maximizing the usage through by-products. The palm oil industry was identified as biomass largest producer, generated nearly 23 million tonnes residues with around 90 % came from plantations whereas the remaining 10 % of oil extraction came from the mills (Padzil et al., 2020). The largest oil palm producer was Malaysia before Indonesia seized the title in 2005 (MPOB, 2014). Development of the oil palm sector in Malaysia grew rapidly due to abundant land and cheap labour cost. Nevertheless, oil palm is still the most important commodity crop in Malaysia.

EFB is another example of non-wood fibre resource that can be a good solution to replace the main fibre resources for pulp and paper making, mainly in Malaysia. One tonne of fresh fruit produces approximately 0.22 tonnes of EFB (Abdullah & Sulaiman, 2013). The main source of cellulosic fibre used in pulp and paper making industry comes from wood. However, due to the scarcity of woody materials in recent years, raw material resources have become one of the major problems in the paper industry. Non-wood fibres from agricultural waste such as bagasse, wheat straw, and bamboo are used as the alternative fibre resources in the field of pulp and paper making (Ferrer et al., 2011). The utilization of non-wood fibres which can be made into a pulp is an effective way in the production of pulp and paper. With the recent development of the oil palm industry, EFB is available as raw fibre material to produce paper-based products. The oil palm waste contributed to the profitable factors to the development of the palm oil sector by maximizing the usage through by-products.

Since Malaysia is the second largest oil palm producer in the world, it contributes to the Malaysian's Gross National Income (GNI) which has a vast amount of biomass products. The oil palm industry in Malaysia accounted for approximately 8 % of GNI, creating one of the significant contributors to the country (Anuar et al., 2018). Malaysian's oil palm industry experienced a slight decline in export value and oil palm-based products due to the imminent threat of palm oil-based biodiesel by the European Union which caused low demand and oversupply (Kushairi et al., 2019). The woodfree paper business using EFB has grown in Malaysia over the past few years with a few start-ups initiating the trend. The market for this woodfree paper business is currently very small, especially in Asia. In Thailand, the utilization of oil palm residues in pulp and paper industry has increased to encourage the government policy of Plan to Develop Oil Palm and Palm Oil Industries from the oil palm cultivation as an important crop (Phoochinda, 2020). On the other hand, Indonesia produced the EFB-based paper products including printed papers and cement bags to reduce the import of waste paper using the EFB fibre through semi-chemical pulping (Risdianto et al., 2016). But through advanced technology, it can be the game-changer in the pricing structure as the pulp and paper making from EFB is cost-efficient compared to other woodfree pulp. The total of woodfree pulp from EFB generated up to 10 % of pulping capacity in pulp and paper making production which keeps increasing faster than wood pulp (Aripin, 2014). The major fibre sources for pulp and paper production are coniferous and deciduous trees followed by other woodfree pulp available in the market.

As one of the main producers of palm oil, the raw material of EFB is virtually affordable and available all year round.

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Utilization of EFB as raw material and transforming it from waste into by-product. The green technology approach of using a non-toxic production process enables the company to use less energy and water. The use of EFB as an alternative raw material for pulp and paper provide added value and contribute to the zero-waste approach to the palm oil industry. On the other hand, through zero-waste approach, energy and electricity consumption can be minimized as against other pulping methods (Daud & Law, 2011). The EFB itself can be used to generate the electricity and steam required to form a pulp sheet. The utilisation of EFB as the raw material promotes sustainability of the oil palm industry in Malaysia as well as zero-waste oil palm production by transforming the oil palm waste i.e. EFB into by-product. Zero-waste oil palm production utilized the oil palm biomass in order to create nanocellulose and nanomaterials, especially in the exploration of nanotechnology (Burhani & Septevani, 2018). The production of fertilizers and fungicides, as well as agro-chemicals could enhance the oil palm yield, stabilize the pest and disease control, and increase the oil extraction rate (Maluin et al., 2020). The EFB is simultaneously available along with the development of the palm oil industry. It is a promising alternative to use as fibre resources in the field of pulp and paper making. Various high-end applications produced from EFB including nanocellulose and nanomaterial-based products such as hydrogel demonstrated better economical values to substitute the synthetic products which are harmful to human health and environments (Padzil et al., 2020). It can be noted that with continuous research into these applications, the utilization of EFB generates new insights for more cutting-edge materials with superior properties. The characteristics and properties of fibres from EFB as well as the utilization of EFB in the pulp and paper making processes are also discussed. Hence, this paper gives an overview of the utilisation of EFB as the raw material in pulp and paper making industry.

2. Characteristics of Oil Palm EFB for Pulp Making

Malaysia has generated a large amount of biomass along with the production process as one of the oil palm major producers in the world market, especially in the utilization of EFB, POME, and palm kernel shell. A total of 1.07 tonnes of oil palm EFB is generated in order to produce 1 ton of palm oil (Aljuboori, 2013). The oil palm EFB is a type of woody biomass with a calorific value of 4,400 kcal/kg-dry and is considered as a non-toxic and promising biomass resource for industrial and farming applications including pulp and paper manufacturing (Harsono et al., 2016). EFB fibre is an unpolluted biodegradable material, non-carcinogenic, and free from impurities that are regarded as waste. The EFB fibres are stable and can be processed into numerous applications based on the definite dimensional grades including erosion control protection, machine cushion production, soil stabilization, landscaping design, ceramic and brick manufacturing, paper production, soundproofing material, livestock, compost, as well as fertilizer (Jinn et al., 2015; Khalil et al., 2012).

EFB is generated when the fruits are removed from the oil palm fresh fruit bunches (FFB) for oil extractions, leaving only stalk and spikelet of the fruit (Figure 1). The steam from the sterilization process of oil extraction combined with continuous biological growth resulted in water saturation in the EFB with a high moisture content of up to 60 % (Faizi et al., 2016). Oil palm EFB fibres consisted of lignocellulosic fibres in which the cellulose (43-65 %) and hemicellulose (17-33 %) are covered in lignin (13-37 %) matrix similar to the other natural fibres (Rafidah et al., 2017). Lignin, cellulose, and hemicellulose contents were almost comparable to soft and hardwood indicating a potential for pulping and producing natural resources fibre (Wahab et al., 2015). Therefore, pre-processing is crucial before the oil palm EFB can be processed into other value-added products.

Figure 1. The raw oil palm EFB

The morphological properties revealed that the EFB fibre resembled greatly the short-fibre hardwoods like eucalyptus, a fast-growing evergreen tree native to Australia (Ferrer et al., 2011). The long and short fibres are cylindrical with gradual tapering ends. The EFB fibres include short fibres to moderate, i.e., between 1-2 mm in diameter while including a group of small to medium diameter (2 to 2.5 µm) (Risdianto et al., 2016). In general, physical and morphological properties of EFB fibres are displayed in Table 1. In this regard, the oil palm EFB fibres have a thicker cell wall compared to the wood fibres, resulting in a noticeably higher rigidity index (Daud & Law, 2011). Hence, the oil palm EFB would be a better choice to produce paper in high bulk with their thick cell wall which is accountable for the excellent tearing resistance.

Table 1. Morphological properties of EFB fibres. Adapted from (Risdianto et al., 2016)

Parameter	End part of EFB stem	EFB fibre tip	EFB fibres
Minimum fibre length, mm	0.63	0.46	0.27
Maximum fibre length, mm	1.81	1.27	1.48
Average fibre length (L), mm	1.20	0.76	0.53
Fibre diameter (D), um	16.89	14.34	14.00
Lumen diameter(l), um	8.04	6.99	-
Wall thickness (w), um	3.49	3.68	-
Runkel ratio (2w/l)	0.87	1.05	-
Felting ratio (L/D)	79.95	53.00	-
Flexibility (l/D)	0.54	0.49	-
Fibres content (%)	72.67	62.47	-
Non-fibres content (%)	27.33	37.53	-
Bulk density, kg/m^3	177.98	-	-

The potential of pulp and paper productions from oil palm EFB in Malaysia has widely explored since the 1990s. Malaysian Oil Palm Board (MPOB), which is also recognised as Palm Oil Research Institute of Malaysia (PORIM) back then is among the pioneer who found the potential use of oil palm EFB for pulp and paper bioproducts. Three different types of pulp from the oil palm biomass i.e. EFB, frond, and trunk, the pulp made from EFB contained the most promising profiles which were having good tear strength, excellent opacity, good bulk and good fold, and good formation (Hassan et al., 1997). Many studies have been conducted to explore the potential of EFB and transform the material from waste to wealth (Rushdan et al., 2007; Szabó et al., 2009). One of the promising potentials is paper-making pulp due to its fibrous crop substance identified as lignocellulosic residues. A high number of fibres weight specifies that the EFB-based paper possesses good printing characteristics well-made sheet formation during the papermaking process. EFB could produce a thin, high-quality white paper and specialty papers including photographic papers and security papers (Bajpai, 2010). The paper made from oil palm EFB can be used for book covers, envelopes, wrapping papers, and shopping bags whereas the long-fibre pulp can be used for composite papers, fertilizer bags, and carton boxes. Over the past decade, the EFB was burned until it became ash in order to be utilized as a fertilizer (Gonzalo et al., 2007). Nevertheless, this practice has been banned due to air pollution and led to the cost-effective ways of EFB utilization.

3. Pulp Making Processes using EFB

The paper manufacturing process consists of two main steps starting with raw material preparation. The first step is converting the raw material (EFB) into a pulp, whereas the second step is converting the EFB pulp into paper. Figure 2 illustrates the general process of pulp making using the EFB fibre.

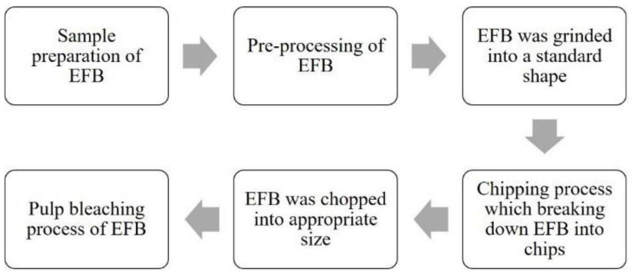

Figure 2. The general process of pulp making using EFB

3.1. Raw material production

Pulp making process begins with raw material preparation and handling. The raw materials have to be grinded mechanically into a standard shape that is appropriate for pulping (Anuar et al., 2018). If the raw material of the pulp is made from wood, the wood logs are first tumbled in drums, a process called debarking to remove the bark (Bajpai, 2010). The raw materials are then sent to grinders, a process called chipping which breaks it down into chips (Sharma et al., 2015). The chips are shifted to a sequence of screens based on the required thickness and length to ensure continuous flow by uniform cooking in the digesters. Typically, the undersized chips are utilized as full waste or passed over into the chip flow process, whereas the oversized chips are re-chipped (Rafidah et al., 2017). The pulp and paper production using EFB as a raw material is generally similar to wood fibre. In the beginning, the EFB is chopped with the purpose of reducing the original fibres to a smaller size.

3.2. Pulp production

Pulping refers to the process that uses chemical, mechanical or semi-chemical ways to remove the unnecessary impurities in the fibre materials. Cellulose and hemicelluloses, the main fibrous components in the paper, are contained around 60-65 % in typical wood (Bajpai, 2016). The remaining materials in wood consist of lignin and ash (Burhani & Septevani, 2018). During the pulping process, lignin is removed from the wood to separate the chips into individual cellulose fibres. The general pulping consists of three different methods which are mechanical, chemical, and semi-chemical pulping.

Mechanical pulping is a method of breaking down the bonds between the fibres by applying mechanical energy to the chips (Hart, 2011). This process uses electricity as the primary source of energy to generate mechanical forces. Maintaining the major aspect of the lignin is the goal in the mechanical pulping in order to ensure the high capacity of pulp with appropriate strength properties and brightness can be achieved. Besides, mechanical pulping produces a higher yield with 90-95 % of the woods will be usable pulp (Bajpai, 2010). Nonetheless, it has a low resistance to aging as the process leaves impurities in the pulp resulting in a tendency to change colour. Furthermore, thermomechanical pulping (TMP) and stone groundwood pulping (SGW) are the common methods used in mechanical pulping (Daud & Law, 2011).

Chemical pulping uses chemicals with appropriate heat and pressure chemical contents to break down the wood pulp (Sharma et al., 2015). The lignin and other materials of the inter fibre matrix material, as well as the lignin in the fibre walls, are dissolved by this process. Hence it allows the fibres to bond together by forming hydrogen bonds between their cellulosic surfaces in the papermaking process (Jinn et al., 2015). In this case, chemical pulps are produced via the cooking process of raw substances using the kraft and sulphite methods. In contrast with mechanical pulping, chemical pulping produces a lower yield, between 40-45 % but the pulp quality is very high (Ogunwusi & Ibrahim, 2014).

Semi-chemical pulping utilizes both chemical and mechanical methods to remove the pulp from the wood (Ferrer et al., 2011). After this process, the wood chips are softened using chemicals, steam, and heated in a digester. After that, the pulp is washed to eliminate cooking liquor chemicals and organic matters dissolved from the chips. Next, the pulp is mixed with 20-35 % recovered fibre or repulped secondary fibre to increase machinability (ETSAP, 2015). The summary of the pulp production process is as shown in Table 2.

3.3. Pulp processing

The next step after pulp production is pulp processing, which is carried out to remove contaminants and to recycle the remaining cooking liquor by means of washing process (Rafidah et al., 2017). The process of pulp impurities removal includes screening, defibreing, and deknotting (Daud & Law, 2011). Drying steps are other important steps to prevent fungal and bacterial growth if the pulp is going to be stored for a long period. Brown stock washer is used when washing the residual cooking liquor from the pulp (Hart, 2011). It is important to have an efficient washing as it can maximize the return of cooking liquor to chemical recovery and reduce carryover of cooking liquor into the next process, which is the bleaching process. The common washing equipment is rotary vacuum washing, diffusion washers, rotary pressure washers, and dilution/extraction washers (Bajpai, 2010). Rushdan (2003) studied the semi-chemical pulping of EFB using the treatments of soda or sulfate by the soda-anthraquinone process. Sharma et al. (2015) developed pilot scale soda-anthraquinone pulping of palm oil EFB using chlorine-free pulp bleaching. In other research, Risdianto et al. (2016) investigated the lipase pre-treatment which was applied prior to the EFB pulp cooking process to reduce the frequency of stain on the paper produced. The pulp making process from EFB has been explored by various approaches such as soda anthraquinone (AQ), alkaline peroxide, acetosolv, and prehydrolysis soda-AQ (Daud & Law, 2011). The results of these studies indicated that the EFB can produce good sheet properties and is very useful for papermaking.

The pulp and paper production using EFB as a raw material is generally similar to wood fibre. In the beginning, the EFB is chopped with the purpose of reducing the original fibres to a smaller size. The pulp of EFB can be produced through the process of semi-chemical pulping by the process of soda or sulfate (Fillion et al., 2006). In addition, before the pulp cooking process can also be applied lipase in pre-treatment to reduce the incidence of pitch (stain) on the paper produced (Daud & Law, 2011). It depends on the final target to be achieved. The process of making pulp from EFB has been investigated by various methods, which are soda, soda anthraquinone, alkaline peroxide, acetosolv, prehydrolysis soda-AQ, and chemical-mechanical (Risdianto et al., 2016). The reaction during cooking dissolves most of the lignin and this lignin retained in the black liquor. The residual product from this process is the fibres which at this stage still contain some lignin. It is subsequently removed by a sequence of bleaching.

3.4. Pulp bleaching

The main objective of pulp bleaching is to increase the brightness of the pulp to produce paper products that emphasise on paper brightness such as printing grades and tissue papers. In contrast, the unbleached pulp is commonly adopted to create products which brightness is not required such as corrugated boxes and grocery bags (Gonzalo et al., 2007). The bleaching process can also solve the yellowing problem of paper by removing the leftover lignin that remains in the unbleached pulp. The reaction during cooking liquefied most of the lignin and this lignin retained in the black liquor (Ogunwusi & Ibrahim, 2014). The residual product from this process is the fibres which at this stage still contains some lignin. It is subsequently removed by a sequence of bleaching. Pulp bleaching process of EFB has been conducted using biobleaching with laccase and xylanase, which is totally chlorine-free (Bajpai, 2010). Therefore, various combinations of chemicals are added to the pulp to remove the colour from the unbleached pulp depending on the desired end products. Mechanical and semi-chemical pulping processes will extract pulps with a high content of lignin. These processes demand a chemical-intensive bleaching process to decolourise the remaining lignin. The most common bleaching chemicals are chlorine, chlorine dioxide, hydrogen peroxide, oxygen, and sodium hypochlorite (Fillion et al., 2006). Each bleaching stage is defined by its bleaching agent, the concentration of agent used, acidity, temperature, and time taken to complete the process as shown in Table 3.

At the final stage, caustic may be used to wash pulp from residual bleaching chemicals and dissolved lignin (Sharma et al., 2015). It then proceeds to a number of screens and cleaners to remove any impurities before the pulp is being concentrated and conveyed to storage. Pulp bleaching process of EFB has been done by various methods including biobleaching with laccase and xylanase, which is totally chlorine-free (Risdianto et al., 2016). The results of these studies indicate that the EFB can produce good sheet properties and is very useful for papermaking. EFB pulp with soda process had produced an industrial scale in Malaysia and is claimed to be suitable for printing and writing paper, corrugated cartons and other paper products. Thus, the utilization of oil palm EFB as raw material for pulp and paper production will provide added value and entailed to the zero-waste approach to the palm oil industry.

4. Paper Production

The development of paper production has led to the high demand for fibre, generating additional concern on the utilization of oil palm EFB for papermaking processes. The continuous supply of oil palm EFB offers a new alternative as a raw source for fibre to substitute the wood-fibre materials in the paper production. Generally, the oil palm EFB pulp is fed directly to the papermaking equipment in an integrated pulp and paper mill (Daud & Law, 2011). On the other hand, the pulp is dried before fed it directly to the papermaking equipment in a stand-alone pulp and paper mill (Szabó et al., 2009). The first step involving the paper making was handling the oil palm EFB fibres. The EFB fibres were cut to a standard size shorter than 30 mm for the overall original fibres obtained from the mills. Semi-chemical pulping was performed using a 50 % concentration of sodium hydroxide solution as the digestion chemical solvent for processing oil palm EFB pulp (Ferrer et al., 2011). The digestion temperature was maintained at 92 °C

Table 2. The types of pulp production, variants and its end-use (ETSAP, 2015)

Type	Variant	End-use
Mechanical pulp	Stone groundwood pulp Thermo-mechanical pulp (TMP)	Used for newsprint and wood-containing papers
Semi-chemical pulp	Semi-chemical pulp	Normally used for tissue production. Chemi-thermo mechanical pulp (CTMP) is used for printing and writing grades
Chemical pulp	Sulphite pulp	May use in newsprint, printing and writing papers, tissue and sanitary papers
	Sulphate/kraft pulp	Used for graphic papers, tissue, carton board, wrappings, sack and bag paper, envelopes and other specialty papers

Table 3. Common bleaching agents and their conditions of use (Bajpai, 2016)

Bleaching agent	Concentration of agent (%)	Acidity (pH)	Temperature (°C)	Time (h)
Chlorine	2.5-8	2	20-60	0.5-1.5
Chlorine dioxide	Approx. 1	0-6	60-75	2-5
Hydrogen peroxide	0.25	10	35-80	4
Oxygen	1.2-1.9	7-8	90-130	0.3-1
Sodium hypochlorite	1-2	9-11	30-50	0.5-3

through indirect heating with saturated steam (Gonzalo et al., 2007).

After the pulping process, the oil palm EFB pulp was washed and refined in a disc refiner. The mixture of EFB pulp with other additives such as titanium dioxide and clay was diluted into the headbox of the paper equipment to adjust the optical properties of the papermaking (Bajpai, 2010). To check the effect of the paper making treatment, a small amount of oil palm EFB pulp was tested in a pilot machine consisting of a press section, dryers, and draining table (Gonzalo et al., 2007). More water was supplied to create a fibre suspension in which the slurry is pumped to the papermaking equipment. The paper mixture was filtered through a moving wire mesh in order to remove excessive water content to produce a paper sheet (Hasibuan & Daud, 2007). The paper sheet formation was performed when the EFB fibres were consolidated into a thin layer. The heated cast-iron cylinders were used during the drying process to reduce the water content by up to 8 % through moving fabric belts (Han et al., 2020).

It was noted that every paper sheet obtained from the paper equipment will not undergo any cleaning process since the pulping already performed the cleaning procedure during the manufacturing process. Blending is a common preparation in paper-making depending on specific mechanical and physical characteristics in order to meet the demand for high-quality papers, particularly for packaging, paperboard, and furniture materials (Rushdan et al., 2007). Other fibres such as kenaf and hardwood kraft pulp have been blended with EFB to achieve higher tensile strength paper (Hart, 2011). Since the paper production heavily relied on the availability of fibre, replacing the wood pulp to EFB pulp could improve the waste management problem and reduce the natural biodiversity loss.

After conducting the drying process, the paper sheets will undergo the finishing treatments by processing it into a paper reel (Szabó et al., 2009). This process is known as super-calendering in which the reel is slit into several parts to cut into the standard size of paper sheets (Bajpai, 2010). Super-calendering is important to improve the lightness, smoothness, and opacity of the papers for the papermaking process. Normally, the super-calendering coating comprises a mixture of binders such as starch or latex to create the desired characteristics according to the paper requirements (Ogunwusi & Ibrahim, 2014). Apart from that, super-calendering is prepared for coated papers and magazines which have a higher smooth surface. In this case, the papers achieved the required surface characteristics through the combination of friction, heat, and pressure as a final process in paper making production (Fillion et al., 2006). Figure 3 shows a schematic diagram for the paper production system. Therefore, the paper industry should focus on the reduction of oil palm EFB production cost as well as increasing the efficiency of unit operations in papermaking equipment.

5. Advanced Application for Pulp and Paper Technology

Oil palm EFB can be regarded as the economical raw material compared to other woody materials. It is able to produce pulp and paper products with good material properties which are abundantly available in Malaysia. Advanced applications for pulp and paper technology have been performed especially for the nanocellulose production from oil palm EFB. Nanocellulose is known for the cellulosic materials with nanoscale dimensions which is non-toxic and biodegradable (Chieng et al., 2017). In order to purify the fibre cellulose, the oil palm EFB fibre was treated chemically since it rich in cellulose contents (Salehudin et al., 2014). Burhani & Septevani (2018) reported the isolation of oil palm EFB nanocellulose fibre using the alkaline solution to achieve the maximum cellulose content. In this sense, low optical properties and surface roughness of paper can be improved by applying the pre-treatment on the refining cycle of paper production.

Nanocellulose hydrogels are one of the products from oil palm EFB that can be produced in various shapes. The potential of oil palm EFB nanocellulose as hydrogels has a promising trend in the fabrication of nanocellulose hydrogels due to the ability of thermal stability to be applied in the pulp and paper technology. Apart from that, EFB cellulose fibre has expanded to meet the demand in low-cost pulp and paper production. The hydrophilic structures of EFB cellulose fiber as well as added-chemicals (halogen ion, metal salt, and metal derivatives) are responsible for the antibacterial activity of the material (Ramli et al., 2014). As a potential material of nanocellulose fibre, oil palm EFB possesses high crystalline content and good mechanical properties. In this case, the cellulose nanocrystals isolation from oil palm EFB can be utilised in pulp and paper production to enhance the physical properties of adhesive material (Setyaningsih et al., 2018). Cellulose fibre obtained from EFB has gained attention due to the unique characteristics such as high strength, excellent thermal properties, low density, biodegradable. According to the specific nanoscale size ration,

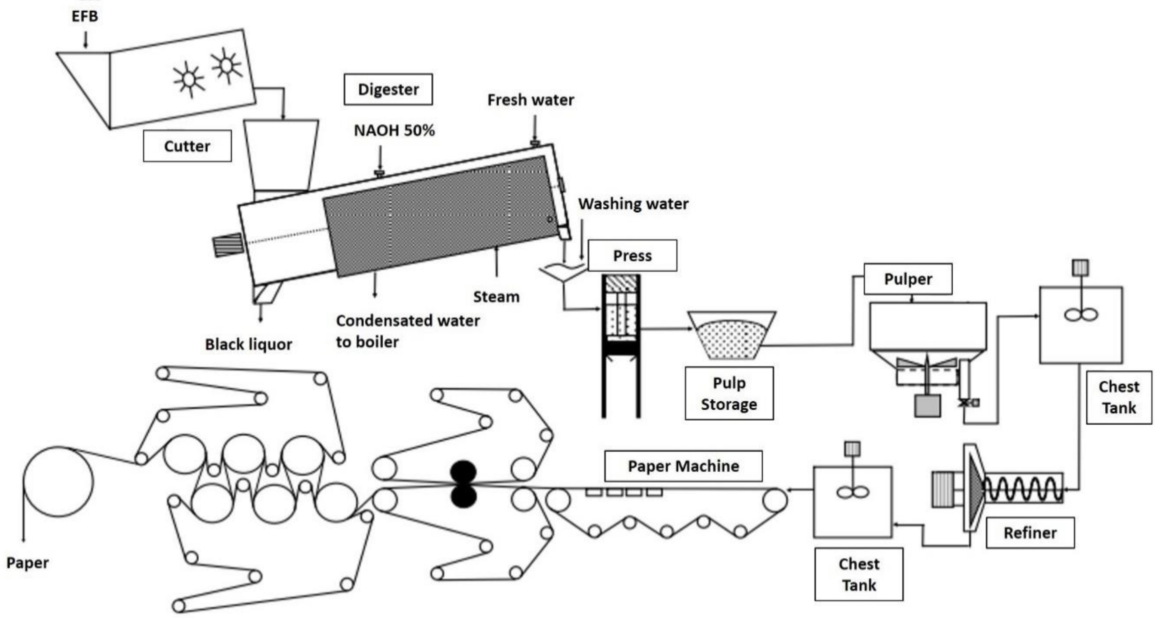

Figure 3. A schematic diagram for the paper production system

the EFB cellulose fiber exhibited an outstanding combination of thermal, magnetic, and optical properties compared to the composite reinforced with micro-sized fibres (Lani et al., 2014).

The abundant of oil palm EFB residues was expected to be increased by approximately 25 million tonnes by 2020 (Jinn et al., 2015). In pulp and paper industries, the EFB cellulose fibre was used as an alternative to minimize the need for the imported recycled fibres which can be transformed into the corrugated board and commercial serviettes. Aqeela et al. (2018) developed antimicrobial papers using EFB with Citronella pulp which was useful for paper packaging industries. In addition, oil palm EFB has gained interest in the polymeric hydrogel because of its benefit as a three-dimensional (3D) cross-linked feature with high porosity. Nanocellulose EFB fibre has also been introduced in the 3D printing technique in recent hydrogel production since it contained high complexity and mechanical strength (Padzil et al., 2020). The 3D printing technique could enhance the hydrogel properties which can also be carried out in bulk amount in single processing. The nanocellulose can be utilized for grafting on the polymerization process which is essential in recent advances for pulp and paper production. Thus, it is a new finding in the hydrogel production using nanocellulose EFB fibre as a potential raw material in Malaysia.

6. Future Trends and Challenges

In Malaysia, oil palm has become a huge industry and this has generated enormous amounts of wastes. One of the wastes is the EFB, and various efforts have been taken by several institutions to convert this into useful products. Currently, EFB is available in large quantities approximately 12.4 million tonnes fresh weight per year and can be supplied continuously from oil palm mills (Wahab et al., 2015). Generally, EFB has high cellulose content (30-50 %) and fibre strength (150-190 MPa) as well as low lignin content (15-30 %) (Cheng et al., 2019; Bonnia et al., 2016). The presence of lignocellulosic in the EFB can be transformed into pulp and paper despite the complex process involving the EFB conversion and organic nature compared to the sources from timber or even recycle paper (Jinn et al., 2015). The papermaking technology has changed significantly over the past few years due to the utilization of EFB as the raw fibre substituting the wood-based materials. There are three components, namely cellulose fibres, lignin, and hemicelluloses that have to be processed as the EFB fibre for paper production (Anuar et al., 2018). The quality of EFB-based paper was constantly developed and high-quality paper can be produced from the raw material. Even though new ways of creating EFB-based products, the cost of production will remain a major aspect of high production lines. It can be noted that the operating costs for pulp and paper production are an additional concern that needs to be addressed between the existing and upcoming trends in the papermaking process.

New applications by upgrading the existing machinery provide more opportunities towards enhancing the efficiency of EFB-based paper production. In this case, the variability and integration of pulp and paper production present more benefits compared to other natural fibre pulp processing which relied on the biomass of wood and other fibre sources. A major contributor to the raw materials comes from the forestry industry, which includes fibre-based chemical pulp-producers, fibre-based boards, and sawmills that produce sawn wood, plywood, and wood-based panels (Szabó et al., 2009). The future of the pulp and paper industry will be governed by the availability of the raw materials and cost of obtaining such items within localized regions. For instance, in a region where recycle papers are abundant and cheap, this will be the primary source of raw materials. In Malaysia, as part of continuous value-added initiatives, the EFB has been identified as a suitable material for pulp and paper making. Nevertheless, there are no policies that ensure constant EFB supply specifically for the pulp and paper industry. The continuous resistance from conservationist and environmentalist groups all over the world may lead to refusal of oil palm related products.

The supply movements of EFB-based papers are difficult to forecast since the EFB was utilized for other products such as textile and building materials with little capacity until 2021–2022 (Berg & Lingqvist, 2019). Particularly, the challenges in escalating the oil palm EFB supply are dealing with the oil palm EFB production assets that require extensive upgrades and further investment in the advance of applications that are less dependent on EFB fibre pulp. The exploitation of oil palm EFB contributes to economic growth which is also related to the pulp and paper industry. For this, a sustainable balanced supply and demand of EFB would be greatly appreciated in order to obtain the best quality of EFB fibre from the combined effluent treatment system. To increase the effectiveness of pulp and paper operation, the incorporation of paper mill equipped with the processing facilities and the oil palm mill operation would ensure the full exploitation of the valuable renewable oil palm EFB. Global production of pulp and paper is estimated to increase gradually, in which by 2030, 50 % of the demand will come from China (Szabó et al., 2009).

Traditional use of paper, such as for business presses and magazines, have fallen in the past recent years due to digital journalism. The future prediction of paper usage is also associated with the global chemical pulp industry. In developing markets where end-use sectors will need more pulp items, another increase is anticipated. Whether the paper and pulp industries are well-positioned for further growth, the paper market demand is also expected to develop into various paper products in the future. The production on EFB-based paper will remain stable since the demand is strong with the increase in activities in e-Commerce industries and other products that still need paper. All in all, the potential market for fibre-based products is set to increase based on the pulp and paper industries in different regions (Figure 4). Common natural fibres available in the market such as kenaf, jute, flax, and sisal have been used in pulp and paper industries for many years due to the renewable and economical values. The other types of common natural fibres have received favourable attraction towards the reinforcement for the polymer composites which has various benefits over synthetic fibres (Khalil et al., 2012). This was mainly due to the fact that the growth prospect of natural fibres has shifted to the global sustainability and commercial applications.

Current trend and technology used in pulp and paper processing are driving the growing demand for eco-friendly fibres used for the pulping process (Kushairi et al., 2019). The increasing demand for EFB fibre in recent years influenced the environmental impact and the feasibility of the technology provider. Nevertheless, the environmental impacts of oil palm cultivation for the future planning of pulp and paper technology need to be taken into account. The main concern for this problem was the availability of EFB fibres for pulp and paper making for a long-term duration. For the short-term duration, improvements should be made to the ongoing oil palm cultivation area in order to produce the optimum capacity for pulp and paper making. In the comparison of EFB with other types of common fibres used in pulp and paper industries in Malaysia, the EFB fibres reported to be a promising material compared to jute or sisal fibres due to the high durability and tensile strength (Khalil et al., 2012). Apart from that, the hybridization of EFB fibres with other fibres could enhance the physical properties of fibre composites used in pulp and paper making process. In terms of mechanical strength, kenaf fibre is stronger and whiter than jute and EFB fibre. As a fibre crop from non-wood pants, kenaf fibre is the most similar to wood pulp. Thus, the utilization of kenaf fibre in the pulp and paper

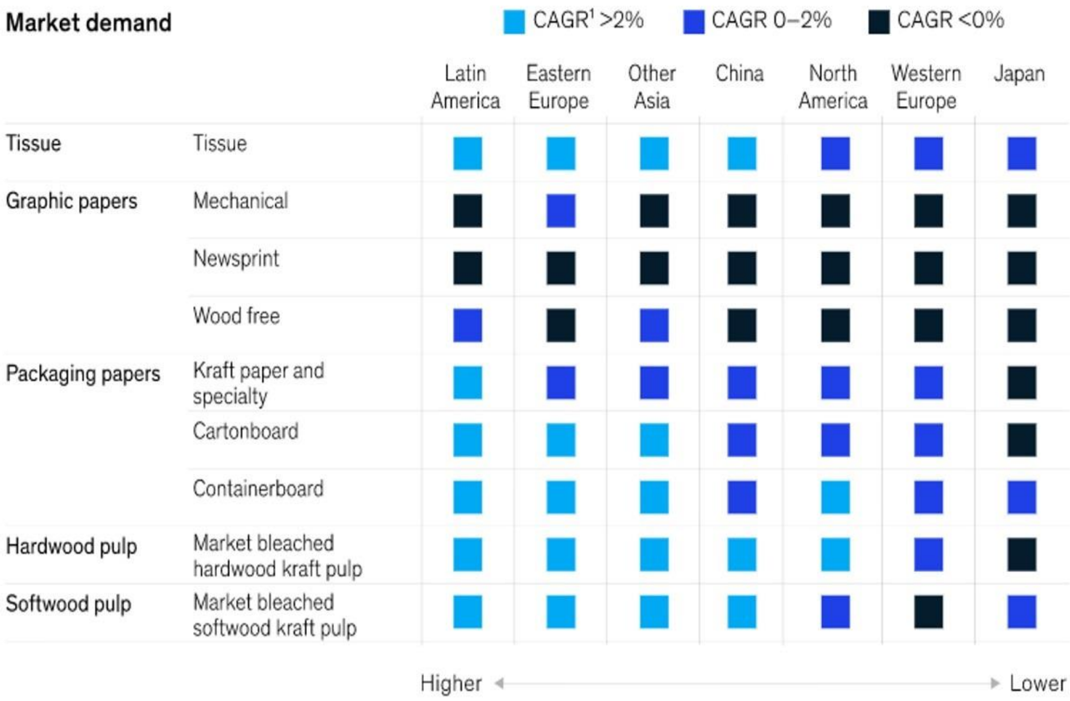

Figure 4. The growth prospect in pulp and paper industries in different regions (CAGR: compound annual growth rate). Source: (Berg & Lingqvist, 2019)

industries are widely used in the pulp and paper industries as well as other industrial applications, specifically in Malaysia.

The EFB-based paper packaging market is multifaceted and constantly developing. Consumer-goods companies, retailers, and policymakers are currently discovering a wide range of possible solutions for EFB-based paper packaging. Consumer packaging will be motivated hugely by demographic modifications and consumer trends that aim for convenience and sustainability. In essence, the declining market on white paper, specifically in light of the latest concerns regarding the use of plastic packaging that could harbour both prospects and challenges for EFB fibre-based consumer packaging. Therefore, the cooperation from both the retailers and consumer-goods companies should be considered in the utilization of EFB-based products considering the future prediction of paper is moving successfully into a new sense of purpose in the paper and pulp industry.

Conclusion

As one of the oil palm main producers in the world market, Malaysia generates a large amount of oil palm EFB, which provides an abundant source of non-wood for pulp and paper making. The use of EFB as an alternative fibre resource of paper production will overcome the limitation of woody materials and meet the needs of environmental issues like deforestation and global warming. The abundant availability of EFB provides opportunities as a potential raw material for pulp and paper making production. It promotes the sustainability of the oil palm industry in Malaysia by transforming the oil palm waste into by-product. In this review, the utilization of oil palm EFB in the sense of fibre characteristics, pulp and paper making processes, as well as advanced applications were elucidated. Advanced applications in the production of nanocellulose EFB fibre, polymeric hydrogel, and antimicrobial papers have been studied to cater the feasibility of the products in pulp and paper technology. With continuous works into these technologies, the development of pulp and paper making processes will be further explored for numerous high-end applications. The great potential shown by EFB in pulp and paper production leads to the expectation that it will be commercialized into various products. Hence, the exploration of oil palm EFB offers vast and promising prospects towards significant advances and improvement in pulp and paper production in Malaysia.

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Author contributions

Maimunah Mohd Ali edited and finalized the manuscript. Nur 'Atirah Muhadi assisted in drafting the manuscript. Norhashila Hashim critically revised manuscript submission. Ahmad Fikri Abdullah and Muhammad Razif Mahadi provided advice in the manuscript revisions.

Conflict of interests

The authors have declared no conflict of interest.

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