Application of Cellulosic Fiber in Soil Erosion Mitigation: Prospect and Challenges

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The agricultural industry is one of the main economic contributors in developing countries, especially in tropical regions. Extensive land clearing has led to severe erosion within the watersheds, which increases the vulnerability of water catchments to natural disasters, such as floods. Cellulosic fibers, such as jute, sisal, kenaf, hemp, and coir, are gaining increasing worldwide attention for their potential application in controlling soil erosion, principally due to their remarkable biodegradable and physical properties. Nonetheless, the research on biocomposites in controlling soil erosion is limited compared to the natural fibers. This is perhaps due to poor availability and high cost of biodegradable polymers compared to natural fibers, which are abundant and inexpensive. Poor adhesive interactions between the matrix and natural fibers due to the hydrophilic characteristic of the fibers is another major drawback that limits the development of biocomposites for controlling soil erosion.

Keywords: Cellulosic fiber; Biomass wastes; Soil stabilizer; biocomposite; Environment; Sustainable

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INTRODUCTION

Awareness of the potential replacement of synthetic polymers with biodegradable sources first arose in the late 1970s. This was due to the oil crisis that occurred during that era and the difficulties in composting synthetic polymers relative to natural polymers (Hatakeyama *et al.* 1977). The proliferation of synthetic polymers and the extensive dumping of such waste into the ocean and landfills have led to various environmental problems, such as the ingestion of plastic materials by wildlife in the ocean and land that ultimately causes fatalities (Huang *et al.* 1990). The United States became the world’s top leader for environmental innovation in the late 1960s, whereas environmental interest and action in Europe began only during the 1980s (Lampe and Gazda 1995). In Asia, Japanese researchers began to replace synthetic plastic with fermented carbohydrate polymers in the 1970’s (Glass) (John *et al.* 1998). Since then, various studies and research have been conducted globally to fully utilize natural resources and recycled waste materials to replace petroleum-based non-biodegradable polymers.

The evolution of natural fiber as a reinforcement material in biodegradable composites has been growing tremendously in industrial and research fields. Natural fiber is a fiber that originates from any natural resource, which includes plants and animals (Ticoalu *et al.* 2010). Natural fibers have good mechanical properties, especially when compared to synthetic fibers (May-Pat *et al.* 2013). Natural fibers, particularly from plants, such as sisal, hemp, flax, bamboo, coconut, kenaf, jute, and ramie (Ticoalu *et al.* 2010), are relatively low density, low weight, low cost, energy-efficient, non-toxic, renewable, recyclable, and biodegradable (Herrmann *et al.* 1998; Wambua *et al.* 2003; Cheung *et al.* 2009; Thomas and Pothan 2009). Therefore, natural fibers are both environmentally friendly and cost-effective.

Natural fibers have been innovatively embedded with biopolymer matrices made up of cellulose, starch, and lactic acid to form biocomposites since the 1980s (Herrmann *et al.* 1998). The biopolymer matrix in a biocomposite functions to stabilize the shape of the structure, transfer the pressure between the fibers, and functions as a coating to protect the composite from damage (Moser 1992; Luo and Netravali 1999). Formerly, biocomposites have been used in packaging and agricultural industries (Herrmann *et al.* 1998). However, due to growing demand, they have also been used in the automotive industry. Due to their equivalent cost with glass fiber-reinforced plastics, biocomposites have also been applied in the building industry as door panels, as they offer aesthetic value and are resistant to scratching and ultraviolet degradation (Marsh 2003).

Today natural fiber has gained attention from various industries due to its abundance availability and good mechanical properties. The scope of this manuscript is to discuss the natural fiber derived from agricultural byproducts and its potential applications as soil cover for erosion mitigation. Various strategies have been implemented to stabilize soil structure, including mechanical, physical, and chemical reaction techniques. Soil reinforcement, soil replacement, compaction, and chemical soil stabilization are some of the techniques to enhance the mechanical properties of soil (Tabatabaee 1985). In review, the efficiency of controlling soil erosion by using natural resources, such as EFB, oil palm frond, eco-mat, and leguminous cover crop plants, are discussed. However, cellulosic-soil mixing strategies are outside of the scope of this manuscript. As well, this review aimed to study the current trends in the applications of biodegradable materials and biocomposites in soil erosion mitigation.

The agricultural industry is one of the main economic contributors to developing countries, such as Malaysia and Indonesia. Malaysia and Indonesia are among the biggest producers of oil palm in the world, with 5.64 million hectares (Malaysian Palm Oil Council, 2015) and 8 million hectares (Indonesia Investments 2016) of plantation area, respectively. Furthermore, these numbers are projected to increase annually. However, in Malaysia, annual flood events have become more severe, particularly in the East Coast of Peninsular Malaysia. Agricultural activities, such as deforestation and the replanting season of palm oil, have been suspected to be main contributors to these flood events (Zafirah *et al.* 2016).

Although the increasing exploitation of oil palm brings many advantages to nations engaged in oil palm cultivation, especially economic advantages, environmental impacts must be considered. During the critical stage of oil palm establishment, the exposed surface soil is most vulnerable to erosion, particularly during the rainy season. Soil erosion is one form of soil degradation and is mainly driven by water and wind factors. Although soil erosion is a natural process, anthropogenic activities can increase rates of erosion up to 40%. Soil erosion leads to surface runoff due to the impact of rainfall. Water runoff transports eroded soil into river basins, which eventually causes sedimentation. In addition to deteriorating water quality and aquatic ecosystems, sedimentation also causes shallowing of water bodies until they can no longer sustain any water loads, which leads to overflow of the water bodies and consequent flood disasters.

Therefore, as soil erosion is a worldwide issue, researchers have studied various initiatives to prevent soil erosion from worsening for several decades (Leknoi and Likitlersuang 2020). Research has been carried out is the application of materials, particularly natural fibers, through various methods, such as mulching, spraying, coating, and matting methods. Borst and Medersk (1957) used manure and straw mulching to increase the infiltration rate of water into soil. In a more recent study, Deshmukh *et al.* (2015) used rice straw blankets to promote vegetation growth and increase soil moisture content. However, the cellulosic material application on soil not only can mitigate the soil erosion, but it can also play important role in pest management if applied systematically (Jabran 2019).

CELLULOSIC FIBER FOR SOIL EROSION CONTROL

The zero burning policy currently employed in many types of plantations is a good example of the development of more sustainable agricultural practices. Therefore, mulching and matting with natural fibers are used in the agricultural industry to control erosion and promote vegetation growth in a wide variety of situations, such as plantations or construction sites (Likitlersuang *et al.* 2020). In general, attributes of natural fibers such as strength, length, biodegradability, stiffness, size, and weight play important role for the effectiveness of natural fiber application in soil erosion.

In general, attributes of natural fibers such as strength, length, biodegradability, stiffness, size, and weight play important roles for the effectiveness of natural fiber application in soil erosion. Today most of natural fibers applied on soils are in the form of geotextile, *i.e.* kenaf, sisal, hemp, and bagasse. Others like jute, oil palm empty fruit bunch (OPEFB), wood fiber, and straw are applied directly (Clark 2010). These approaches are employed because they are cost-effective, provide a nutrient supply, and increase the organic matter content in soil with minimal usage of fertilizers and pesticides. The strength and weaknesses of cellulosic fibers used to control soil erosion, *i.e.* jute, kenaf, oil palm empty fruit bunch, hemp, coir, wood, and straw, are compared and summarized in Table 1.

Jute Fiber

Jute is a natural fiber that is long, shiny, and golden in color, and it is commercially obtained from two species, which are the white jute plant (*Corchorus capsularis*) and the tossa jute plant (C. *olitorius*). Jute fibers, which are mainly comprised of cellulose and lignin, are extracted *via* a natural microbial process known as retting (Gupta *et al.* 1976; Majumdar and Day 1977). Retting is an important process, as the quality of the jute fibers is largely dependent on retting efficiency (Chi *et al.* 1966; Ahmed and Akhter 2001). Retting involves the immersion of jute bundles in slow running water, such as a channel, streamlet, tank, lake, or reservoir, for 14 d to 28 d to break down the pectin materials, hemicellulose, and lignin (Banik *et al.* 2003; Paridah *et al.* 2011). However, as the retting process causes environmental pollution and heavy competition in the fiber market, innovative methods have been introduced to enhance final product quality, reduce labor needs, and decrease the costs (Jahan *et al.* 2016) of jute production.

The Bangladesh Government has recommended a ribbon retting method that improves fiber quality (Banik *et al.* 2003), requires half the amount of water needed in conventional retting, shortens production time by 4 d to 5 d, and reduces environmental pollution (Alam 1998). The production of jute is mainly concentrated in India, China, and Bangladesh. Jute fiber is in high demand due to its availability, durability, biodegradability, low thermal conductivity, and fiber uniformity. In India, jute has been traditionally used for packaging materials, such as strings, hessian, carpet backing, gunny bags, and canvas.

Jute is used globally in diverse industries, which include the automobile, construction, transportation, furniture, textile, and cosmetic industries (Gon *et al.* 2012; Jirawattanasomkul *et al.* 2019)

In addition, jute fiber is used in the agricultural industry for land restoration during the process of natural vegetation establishment. The fiber is applied alone or blended with other polymers (both natural and synthetic). Jute geotextile is used for various civil engineering applications, such as controlling topsoil erosion, protecting river and canal banks, stabilizing slopes, and strengthening road pavements (Jadvani and Gandhi 2013). A case study in India found that, when compared with synthetic erosion control materials, jute geotextiles increased vegetative cover 80%, retained soil nutrients and soil moisture, and reduced maximum dry density (Barooah and Goswami 1997; Datta 2007; Mathur *et al.* 2008; Jual and Sharda 2008; Aggarwal and Sharma 2010; Islam *et al.* 2013; Sonthwal and Sahni 2015). This was due to the capacity of jute geotextiles to retain 375% more water than their dry weight (Islam 2013), which increased the shear strength of the soil (Zaidi *et al.* 2016) where the root system of plants anchored the soil together, which decreased soil erosion. Jute geotextiles have also been reported to foster vegetation growth due to their outstanding hydrophilic property of absorbing 4.5 times to 6 times more water more than their dry weight (Rickson and Loveday 1998). Due to their various characteristics, jute geotextiles can fully stabilize a slope in only 1 y (Choudhury and Sanyal 2010). Jute net absorbs raindrop impacts and kinetic energy, which reduces surface runoff and its erosion potential (Ingold and Thomson 1990; Mathur *et al.* 2008) and adds nutrients to the soil upon its decomposition (Mathur *et al.* 2008).

Kenaf Fiber

Kenaf or roselle (*Hibiscus cannabinus*), which is widely commercialized in the southern United States (Kugler 1996; Webber, III *et al.* 2002) is also known as Java jute, due to its similarity with jute fibers (Feng *et al.* 2001). Kenaf is comprised of cellulose (the main reinforcing element), lignin, and hemicellulose, which are the binding elements (Feng *et al.* 2001). Kenaf is a popular cellulosic source that has economic and ecological benefits (Nishino *et al.* 2003). It is a biennial herbaceous plant that takes 2 y to complete its biological lifecycle. Kenaf can grow under a wide range of weather conditions and can reach a height over 3 m three months after sowing the seeds (Terry and Reichert 1999). In South Africa, the United States, and Malaysia, kenaf is typically cultivated for its fiber, which is traditionally used to manufacture ropes and sacks.

Kenaf is unique because the stem produces two types of fiber, including coarser fibers (bast fiber) and finer fibers (core fiber), which are located in the outer layer and inner layer, respectively. Bast fiber comprises 35% of the kenaf plant, and the rest of the plant is comprised of core fiber (Sellers *et al.* 1993). The properties of kenaf fiber are dependent on the sources, age, separating technique, and history of the fibers (Akil *et al.* 2011). In addition to its other uses, kenaf fiber is used as an alternative raw material to manufacture paper (Akil *et al.* 2011), non-woven mats in automotive industries (Magurno 1999), textiles (Ramaswamy *et al.* 1995), and mats for grass seeding and erosion control (Kaldor *et al.* 1990; Ramaswamy and Easter 1997; Webber, III *et al.* 2002).

The kenaf plant has the potential to reduce soil erosion due to its dense and deep root system that holds soil particles together (Lauriault and Puppala 2009). In 1994 and 1995, the United States Department of Agriculture (USDA) spent approximately $100,000 to study the structural composite of kenaf fiber and its application in controlling soil erosion (Kugler 1996). The low water absorption characteristics and good mechanical properties of kenaf fiber make it a good candidate for soil reinforcement (Artidteang *et al.* 2012). Artidteang *et al.* (2012) studied the impact of kenaf geotextile's waving patterns on soil reinforcement applications, and the results demonstrated that the plain pattern of woven kenaf has the highest tensile strength, followed by hexagonal and knot-plain patterns.

Oil Palm Empty Fruit Bunch (OPEFB) Fiber

The oil palm (*Elaeis guineensis*) tree, which is commonly used in commercial agriculture to produce palm oil, has a life-span of 25 y to 30 y and can grow up to 20 m in height. It is cultivated, produced, and commercialized worldwide but mostly by Malaysia and Indonesia, which together account for approximately 85% of global palm oil production (Indonesia Investment 2016). An oil palm tree consists of approximately 90% biomass waste and 10% oil. Every year, billions of tonnes of waste products, particularly OPEFB and palm oil mill effluent (POME), are produced after the sterilization and stripping process of fresh fruit bunches (FFBs) (Abdullah and Sulaiman 2013). For every ton of crude palm oil (CPO) produced, 1.1 tons of OPEFB is disposed of (Karina *et al.* 2008) due to the difficulty of managing these wastes (Abdullah and Sulaiman 2013).

This abundant major byproduct is sometimes disposed of *via* incineration, which causes extensive air pollution. Oil palm empty fruit bunch, which is primarily comprised of cellulose, hemicellulose, and lignin (with cellulose contributing the highest percentage of biomass of 49% to 65%), offers the best prospects to be an effective reinforcement material in composites (Rozman *et al.* 2000; Sreekala *et al.* 2004; Norul Izani *et al.* 2013). Many studies have been conducted to sustainably utilize biomass wastes from the oil palm industry. Among these studies, the use of OPEFB in the pulp and paper industry to replace the existing paper from wood sources was explored (Ibrahim 2003; Tanaka *et al.* 2004).

Studies have also been carried out on the application of OPEFB as a raw material for the production of various materials, such as super capacitor electrodes (Farma *et al.* 2013), glucose, and xylose (Lim *et al.* 1997; Rahman *et al.* 2006), activated carbon (Alam *et al.* 2007), bio-diesel (Feng 2013), bioethanol (Sudiyani *et al.* 2013; Chiesa and Gnansounou 2014), and microbial oil (Ahmad *et al.* 2016). Conventionally, EFB is used as mulching material. Empty fruit branch can also be incinerated to obtain oil palm ash (OPA), which has a high potassium content (Thambirajah *et al.* 1995; Husin *et al.* 2002; Farma *et al.* 2013) and can be applied as soil conditioner and organic fertilizer in estates and plantations. When applied as a soil conditioner, EFB increases the soil's pH, cation exchange capacity, soil moisture, organic carbon, and nutrient contents (Teh *et al.* 2010; Comte *et al.* 2013; Frazão *et al.* 2014), and can thus function as a replacement for chemical nitrogen fertilizers, which tend to increase the acidity of the soil in oil palm plantations due to the removal of base cations (Nelson *et al.* 2011).

Upon decomposition, OPEFB acts as a compost fertilizer that aids nutrient cycling, primary productivity, and soil carbon stabilization (Hättenschwiler *et al.* 2005; Tao *et al.* 2016). Compost fertilizers derived from OPEFB also enhance soil fauna feeding activity through the presence of decomposer microbes, and they increase the concentration of base cations and soil moisture, which improves soil quality (Tao *et al.* 2016). Empty fruit bunch can retain water and release it gradually into the soil, and it can improve soil fertility and productivity due to better aeration and decrease soil erosion due to the improvement of the physical and chemical characteristics that contribute to sturdy soil structure (Abdullah and Sulaiman 2013; Syakir *et al.* 2016).

Sisal Fiber

Sisal (*Agave sisalana*), which constitutes 2% of global plant fiber production, originates from southern Mexico and is extensively cultivated and naturalized in many other countries, particularly in tropical and subtropical countries with temperatures above 25 °C, and it has a life span from 7 to 10 years. It cannot be cultivated in moist, saline soil conditions, such as clay. Each of its sword-shaped leaves consists of approximately 1000 fibers, which constitutes 4% of the total fiber in the plant. Sisal fiber is extracted by stripping off the leaves using a rotating wheel set with blunt knives. The drying process is the most crucial part, as moisture content determines the quality of the fiber. Although artificial drying is reported to yield better grades of fiber compared to sun drying, it is not practical in developing countries where sisal is produced. The sisal fiber is traditionally used for manufacturing string, rope, and twine. Presently, sisal fiber is used in the automotive industry as a strengthening agent in composite materials and in the paper industry due to its high cellulose and hemicellulose contents.

Sisal fiber is also used for marine and agricultural cordage and in the carpet and textile industries. In addition, Sisal fiber is used to make sisal geotextiles, which are designed to protect soil by creating a micro-climate for seedlings until vegetation is established. Sisal fiber has a longer life span than jute; thus, sisal geotextiles are beneficial when applied on riverbanks or for extreme applications where plant growth is gradual (Smith 2000). When tested on a 17% land slope, sisal geotextile demonstrated better erosion control than jute and coir geotextiles due to its high-water absorption capacity (Ram *et al.* 2009). Similar to kenaf fiber, sisal fiber has low moisture absorption (Giridhar and Rao 1986; Methacanon *et al.* 2010) and high strength (Methacanon *et al.* 2010).

These two unique properties indicate the good performance of sisal geotextiles, as strength and durability are vital characteristics in soil erosion control (Methacanon *et al.* 2010). Sisal fiber reinforced soils with cement increased the tensile behavior (Mattone 2005; Mwasha 2009) and decreased the bulk density of soil (Mattone 2005). Sisal fiber also significantly improved the shear stress of soil *via* earth reinforcement, as an increase in fiber length reduces the shear stress, which leads to the interlock failure between soil and fiber particles to cooperate as a single coherent matrix (Prabakar and Sridhar 2002).

Hemp Fiber

Cannabis sativa or hemp is typically found in the northern hemisphere and grows to a height of 6 to 12 ft. It is cultivated for the industrial uses of its derived products, including its stalk, which consists of two type of fibers, long fibers (bast) and short fibers (core). In contrast with other trees, hemp is ready to be harvested 2 to 4 months after being planted. In addition, it can grow in most types of soil and climates with moderate nursery management. Extraction of hemp fiber can be completed by two methods, which include retting (traditional method) or thermo-mechanical pulping (modern method). There have been controversies regarding the prohibition of cultivation and usage of hemp fiber in the U. S., as it was claimed to be the main source for the recreational drug marijuana. However, it has been verified that industrial hemp and marijuana come from different breeds of *Cannabis sativa*. Thus, industrial hemp has no value as a recreational drug (Yonavjak 2013). The superior properties of hemp fiber, such as its strength, durability, and absorbency are currently in demand in a wide range of industries and applications. It is typically blended with other fibers, such as wheat straw or flax, to increase its mechanical properties for use in textiles, rope, twine, paper, and building materials.

Hemp fiber is also used to control soil erosion. Geotextiles made from hemp fiber are designed to prevent soil erosion by stabilizing new plantings while they develop root systems along the slope, thus reducing the growth of weeds on bare soils. However, unlike geotextiles made from coir fiber, hemp degrades rapidly over a few months when exposed to water and soil, which makes it unsuitable for long-term applications (Karus *et al.* 2000). However, Small and Marcus (2002) disapproved of this statement and stated that a long-life span is an undesirable attribute in geotextiles, and the most vital aspect is the choice of a vegetation crop type that has the ability to develop root systems in a short period of time (Lekha 2004). The hemp plant possesses long tap roots that help to hold soil particles together, inhibit soil erosion, and increase soil aeration. Organic matter originating from hemp plants also improves soil fertility and helps decrease the usage of fertilizers in farmland. In this way, soil damaged by compaction and erosion can be repaired and restored. In addition, this method can reduce nitrogen pollution in water bodies due to soil leaching.

Coir Fiber

Coir or coconut fiber is extracted from the mesocarp tissue or husk of the coconut (*Cocos nucifera*). One thousand coconuts can supply enough raw material to produce 10 kg of coir. Coir fiber has high concentrations of lignin and lower decomposition rates than other natural fibers, which makes it the most suitable candidate for outdoor applications. Coir fiber can be divided into two types: brown fiber and white fiber. Brown fiber is extracted from mature coconuts and thus contains more lignin and less cellulose, whereas white fiber is extracted from immature green coconuts, which causes it to be smoother and finer but less durable. Conventionally, retting is conducted for several months to extract coir from coconut fruits. As technology has advanced, coconut defibering machines have been widely used on account of their practicality and time efficiency.

Coir fiber is used in rope, sack, brushes, doormats, rugs, insulation panels, packaging, and automobile body panels. Typically, brown coir is more frequently used than white coir due to its high durability. Coir fiber is an abundant and renewable resource with a very low decomposition rate as and higher shear stress than other natural fibers, which makes it suitable for controlling soil erosion. In a soil burial test with identical soil humidity and temperature conducted by the German Federal Institute for Material Testing, cotton and jute fibers took only 6 w and 8 w, respectively, to disintegrate, whereas coir fiber took more than a year to degrade (Rao 2002). In addition, it has an outstanding tensile strength that is resistant in various climates and conditions (Karus *et al.* 2000).

Geotextiles made from coir fibers were reported to successfully initiate vegetation growth in a short period of time due to the presence of sufficient water and light that encouraged seed germination. Compared to flax and hemp fibers that disintegrate rapidly in a few months, coir fiber has long-term stability due to its high lignin content (40% to 50%) and low cellulose content, and it is cheaper than flax and hemp fibers (Gupta 1991; Pritchard 1999; Karus *et al.* 2000). The tensile strength of coir geotextile decreases to 70% after 7 months of application (Vishnudas *et al.* 2008). Vishnudas *et al.* (2012) stabilized cultivated slope land by using coir geotextiles and found that slopes with crops treated with geotextiles had higher moisture content and less soil erosion than the control plots with geotextiles alone and no crops.

In addition, coir fiber is naturally resistant to seawater; therefore, it can be used to protect coastlines from erosion and prevent further deterioration along shores. It also has high endurance against high velocities of water flow and is suitable for application on steep slopes, as it increases soil water infiltration and provides sufficient protection from erosion by impeding rapid water flow (Gupta 1991). For instance, compared to unprotected soil, coir nettings decrease soil erosion 99.6% during the pre-monsoon season, 95.7% during the monsoon season, and 78.1% during the post-monsoon season (Lekha 2004). Beyond the enhanced infiltration of soil, coir-based rolled erosion systems delay the time for soil runoff, reduce intensity of rill incision, and reduce soil loss compared to bare soil (Sutherland and Ziegler 2007). Yadav and Tiwari (2016) reinforced clay soil with alkaline-treated coir fiber (1%) and pond ash (10%). They found that the addition of pond ash and fiber decreases the dry unit weight and increases water retention capacity, compressive strength, split tensile strength, and axial strain at failure of soil mixtures. Lekha (2004) found that soil structure is improved and the total organic carbon content in soil is enhanced through the application of coir fiber.

Bagasse

Sugarcane (*Saccharum officinarum*) can grow up to 3 m to 5 m in height and is typically cultivated in tropical and subtropical climate zones, such as China, Brazil, and Thailand. The sugarcane plant produces sugar (mainly in the form of sucrose). The fibrous waste residues that remain after the squeezing of sugarcanes during sugar production are known as bagasse. Generally, bagasse contains approximately 40% to 60% cellulose (Alavez-Ramirez *et al.* 2012). Globally, the output of bagasse fibers is estimated to be 75 million metric tons per year (Rowell 1998). Bagasse is currently used in various industries such as the construction, packaging, disposable tableware, paper and pulp, agricultural, and fuel industries. In addition, bagasse is used to generate heat and electricity in sugar mills, to control soil erosion by mulching, and produce geotextile mats (Fortes *et al.* 2012; Carvalho *et al.* 2013). Bagasse mulch improves carbon and nutrient cycling (Fortes *et al.* 2012), water retention (Dourado-Neto *et al.* 1999), and the structure of the soil (Graham *et al.* 2002). In addition, bagasse contains beneficial nutrients needed by plant growth, including N, P, K, and Ca (Graham *et al.* 2002; Fortes *et al.* 2012; Trivelin *et al.* 2013).

Bagasse geotextiles are among the natural fiber geotextiles that are fully biodegradable due to their high lignin content, which provides a natural adhesive to entangle the fiber mat together (Collier *et al.* 1997). The cited authors found that bagasse mat maintained its superior structure even after being tested in heavy rains, whereas woven coir net shrank after the first rainstorm. However, bagasse mats have a slow vegetation growth rate due low light penetration. Dang *et al.* (2016) found that the mixture of bagasse fiber and hydrated lime enhanced the compressive strength of expansive soil.

Wood Fiber

Wood fibers are cellulosic elements that are obtained from trees and commonly used to make various materials, including paper. Typically, wood fibers are used in the paper and pulp, construction, and wood industries. They are also applied to control soil erosion. Hydraulic mulch is a temporary way to protect exposed soil from erosion with a mixture of shredded wood fiber and a stabilizing emulsion (California Stormwater Quality Association 2003). Isrealsen and Urroz (1990) tested the efficiency of different mulches (wood fiber/tack, silva fiber, straw tack, and regular fiber) in preventing soil erosion by using a rainfall simulator. Results revealed that wood fiber/tack mulch had the lowest soil erosion rate after silva fiber, whereas straw tack mulch showed the highest soil erosion rate of the remaining mulches.

Water runoff rate was also notably reduced by the wood fiber/tack mulch, followed by silva fiber, straw tack, and regular fiber mulches. The data for the germination of barley seeds, the dry weight, and height of the barley plant showed that the wood fiber/tack mulch and the silva fiber mulch were superior to the straw tack and regular fiber mulches. This was due to the greater degree of seed protection provided by these mulches, which encouraged germination of seeds under warm temperatures. The study also found that long-fibered products performed better than short-fibered ones, whereas products with tackifiers were more efficient than products without tackifiers.

The authors included a disclaimer that the results presented were not conclusive due to the small number of replications (Isrealsen and Urroz 1990). Prats *et al.* (2017) added that sieved wood fiber was more effective in reducing soil erosion, as a smaller fraction of shredded wood led to a lower soil erosion mitigation capacity and was less cost effective than sieved wood fiber for large-scale applications (Foltz and Wagenbrenner 2010). Mulch application at a rate of 2.6 Mg ha^{-1} over 70% ground cover significantly reduced soil erosion and resulted in less formation of drainage channels during intensive rainfall.

Straw

Agricultural straw is one of the most frequently used materials for soil erosion mitigation, as it is commonly recognized to be the most practical, cheapest, and simplest way to impede soil loss (Foltz and Dooley 2003). Past studies mainly evaluated the effects of straw mulching on the stability of post-fire soil. Straw mulching is more viable than erosion barriers for decreasing soil erosion after severe wildfires, despite low rate application (Fernández and Vega 2016). Many studies agree that at least 60% of ground coverage is exposed to soil erosion after fires (Johansen *et al.* 2001; Vega *et al.* 2005; Cerdà and Doerr 2008). In agreement with Vega *et al.* (2014), straw mulch that covered approximately 60% of the affected area reduced soil erosion 70% during the first month after the fire, whereas erosion barriers reduced soil loss by only 32% during the first year of application and decreased rapidly afterwards (Fernández and Vega 2016).

However, Fernández-Fernández *et al.* (2016) claimed that straw mulching has no remarkable impact in reducing soil erosion, which may be due to the moderate rainfall intensity and erosion rates at the time the study was conducted. Prosdocimi *et al.* (2016) stated that the use of straw mulch resulted in delayed ponding and runoff generation and decreased median water and sediment concentration runoff, which consequently reduced soil erodibility and surface runoff overall. In addition, straw mulching increases water retention, organic content, and the availability of nutrients in soil, which improved the production yield of the crops (Stagnari *et al.* 2014). In a study conducted by Muñoz *et al.* (2017) on the physicochemical properties of soil, the application of a plastic mulching system showed positive impacts relative to straw mulching, such as high soil carbon content and soil stability.

However, the eco-physiological conditions for bacteria growth under plastic mulching were less suitable than under straw mulching, where there was a decline in the number of bacteria and soil fungi and an increase in the production of mycotoxins as a stress sign response by the fungi. Although straw mulch is widely available and has a low specific weight, recent studies have revealed the downsides of straw mulch, which include that its low specific weight allows it to be easily removed by strong winds (Robichaud *et al.* 2014). In addition, it decomposes easily, especially when compared to wood fibers (Robichaud *et al.* 2014; Fernández and Vega 2016).

Table 1. Strengths and Weaknesses of Natural Fibers from Past Studies

Type of Natural Fiber			References
Jute	Strengths	Cost-effective	Mathur *et al.* 2008; Prodhan 2008
		Easy to blend with other fibers	Prodhan 2008
		Environmentally friendly, and is a biodegradable, renewable source of energy	Mathur *et al.* 2008; Prodhan 2008
		Easy installation that does not require expertise	
		Increases the productivity value of land	
		Can maintain water storage capacity in dams and reservoirs	
		Better sturdiness, high tensile strength, heat resistivity, and high porosity	Hamid and Shafiq 2017
		Increases the hydraulic conductivity of soil	Sanyal 2008
		High mechanical properties	Prodhan 2008
		High water absorption and water retention	Aggarwal and Sharma 2010; Kumar and Jagan 2016
		Increases the growth rate of vegetation	Choudhury and Sanyal 2010
		Long life span	Kumar and Jagan 2016
		Degrades within 1 year to 2 year	Choudhury and Sanyal 2010
		Suitable for separation, reinforcement, filtration, and drainage purposes; it is comparable to synthetic geotextile	Mathur *et al.* 2008
		Good reinforcement material	Kumar and Jagan 2016
	Weaknesses	Swells and degrades within six months of immersion in water, is fragile in acidic, alkaline, and other solutions, and has rapid biodegradability	Prodhan 2008
		Results in decreased permeability and penetration of soil	Ghosh *et al.* 2014; Zaidi *et al.* 2016
Kenaf	Strengths	Accumulates carbon dioxide in high concentration and absorbs nitrogen and phosphorus from soil	Michell 1986
		Low density, high mechanical properties, recyclable	Mohanty *et al.* 2000; Nishino *et al.* 2003
		Good reinforcement material	Nishino *et al.* 2003
		Grows well in a wide range of climate and soil types (*e.g.*, high organic peat soil to sandy desert soil)	Dempsey 1975; LeMahieu *et al.* 1991; Terry and Reichert 1999

		High tolerance to drought conditions	Webber, III *et al.* 2002
		High protein content, good digestibility, and may be pelletized	Webber, III and Bledsoe 1993
		Low moisture absorption and high strength	Artidteang *et al.* 2012
	Weaknesses	Uneven fiber distribution	Zampaloni *et al.* 2007
		Cost depends on the quality and cleanliness of fiber (ranging from RM 1.43 to RM 3.81 per kg)	Feng *et al.* 2001
		Form weak bonding interactions with other materials and have high moisture absorption	Tserki *et al.* 2006; Edeerozey *et al.* 2007
OPEFB	Strengths	High availability and low cost	Rozman *et al.* 2000
		High toughness	John *et al.* 2008
		Good resistance to oxidation and heat	Sumathi *et al.* 2008
		Contains few carbohydrates and has a low risk for termite attack	Zaidon *et al.* 2008
	Weaknesses	Low wettability and lack of adhesive penetration due to the presence of residual oil	Paridah and Zaidon 2000
Sisal	Strengths	Longer life span than jute	Smith 2000
		Higher tensile strength than coconut fiber	Kirby 1963; Mwasha 2009
		More compact structure than jute fiber	Giridhar and Rao 1986
		Locally accessible, can be manufactured by small-scale industry, and requires minimal inputs and management	Ram *et al.* 2009
	Weaknesses	Higher cost than jute	Giridhar and Rao 1986
		Poor interaction between fiber and resin in composites	Giridhar and Rao 1986
Hemp	Strengths	High tensile strength and wet strength	Lekha 2004
		High durability, easy to produce, lightweight, not flammable, and resistant to weather	Hutmacher *et al.* 2015
	Weaknesses	Short life span	Karus *et al.* 2000
Coir	Strengths	High durability, high resistance to seawater, abundant, low decomposition rate, and high shear stress	Rao 2002
		High tensile strength	Karus *et al.* 2000
		Initiates vegetation growth in a short period of time, has long term stability, and is affordable	Gupta 1991; Pritchard 1999; Karus *et al.* 2000

Bagasse	Strengths	Very stable and sturdy, good thermal properties (suitable at -25 °C to 220 °C), decomposable, and has high water resistance	Collier *et al.* 1997
		Low cost and simple treatment methods	Dinu 2006
		Availability of raw material	Collier *et al.* 1997
	Weaknesses	Lower light penetration that slows the germination of seeds relative to straw and wood geotextiles	Collier *et al.* 1997; Thames 1997
Wood	Strengths	Wood fiber mulch provides maximum protection for seeds to germinate	Isrealsen and Urroz 1990
	Weaknesses	Short life span, requires 24 h to dry before rainfall occurs and requires a second application to remain operative in rainy season	California Stormwater Quality Association 2003
		May be less effective than straw, may reduce vegetation establishment if applied too thickly, easily washed or blown away, and more expensive than straw mulch	Rivas 2006
Straw	Strengths	Cheap, widely available, practical, and easy to use	Foltz and Dooley 2003
		Lower degradation rate than bark strands	Fernández and Vega 2013
		Efficiently reduces erosion immediately after application	Prosdocimi *et al.* 2016
	Weaknesses	Degrades rapidly, may introduce weeds, and is easily removed by wind and water due to light weight	Robichaud *et al.* 2014; Fernández and Vega 2016

Table 2. Chronology of Soil Erosion Control Using Raw Natural Fibers

No.	Soil Erosion Mitigation Method	Type of Soil	Slope Steep-ness	Type of Erosion	Categories of anti-erosion strategies	Results	References
1.	Manure and wheat straw mulching	Gray brown podzolic Canfield silt loam	2% to 3%	-	Direct spreading of fibers on soil	Manure mulch reduced soil erosion from 12.2 tons per acre to less than half a ton. Straw mulch increased water infiltration, which reduced soil erosion.	Borst and Medersk 1957
2.	Straw, gravel, and soil treated with dioctadecyl dimethyl ammonium chloride (DDAC)	Austin clay	4%	-	Mulch that is composed of fibers and other ingredients	Straw and gravel mulches increased water filtration, reduced runoff, and eliminated erosion.	Adams 1966
3.	Straw mulch	Fox loam soil (Typic Hapludalf)	15%	-	Direct spreading of fibers on soil	Straw mulch was highly effective in reducing erosion even when used in small amounts.	Meyer *et al.* 1970
4.	Straw mulch	Russell silt loam (Typic Hapludalf)	2%, 6%, 12%, and 20%	Interill	Direct spreading of fibers on soil	Straw mulch was highly effective in reducing erosion even used in small amounts.	Lattanzi *et al.* 1974
5.	Rice (*Oryza sativa*) straw	Clayey keletal, kaolinitic, ishyperthermic Oxic Paleustalf	5%	-	Direct spreading of fibers on soil	Increases in the mulch rate reduced soil degradation rates by enhancing soil structure and water infiltration.	Lal *et al.* 1980
6.	Corn and soybean residues	Silty clay loam soil and silt loam soil	5% and 10%	-	Direct spreading of fibers on soil	20% coverage of either residue on soil reduced soil loss by more than 50%. Corn residue was more efficient than soybean in controlling soil erosion.	Dickey *et al.* 1985
7.	Sorghum and soybean residues	Sharpsburg soil	6.4%	Rill & interill	Direct spreading of the fibers on soil	Increased surface cover caused reduction of runoff, sediment concentration, and sediment loss.	Gilley *et al.* 1986

8.	Corn residues	Monona soil	5.2%		Direct spreading of the fibers on soil	Soil loss rate, runoff, and sediment concentration decreased as the amount of corn residues increased.	Gilley *et al.* 1986
9.	Rice straw mulch	Alfisols	-	-	Direct spreading of the fibers on soil	Straw mulch absorbed the impacts of rainfall and avoided the break down and dispersion of soil aggregates.	Perrier 1987
10.	Phosphogypsum (PG)/anionic polyacrylamide (PAM) (spraying method)	Sandy loam soil, Typic Chromoxerert, Typic Rhodoxeralf, and Calcic Haploxeralf	15%	-	Mulch that is composed of fibers and other ingredients	The addition of PAM and PG significantly increased soil infiltration and reduced erosion compared to the addition of PG only.	Smith *et al.* 1990; Levin *et al.* 1991
11.	Farmyard manure and rice straw	Patancheru series	2%	Splash	Mulch that is composed of fibers and other ingredients	Rice (*Oryza sativa*) straw significantly reduced soil runoff compared to farmyard manure.	Smith *et al.* 1992
12.	Anionic PAM, cationic polysaccharide (PSD)	Calcic Haploxeralf and grumusol (Typic Chromoxerert)	15%	Interill	Mulch that is composed of fibers and other ingredients	PAM treatment significantly reduced soil losses and increased infiltration compared to PSD treatment.	Levy *et al.* 1992
13.	PAM (spraying method)	Calcic Haploxeralf and dark brown grumusol (Typic Chromoxerert)	5%	Rill	Mulch that is composed of fibers and other ingredients	PAM reduced soil loss approximately 94% and increased infiltration approximately 15% when applied at rates of more than 0.7 kg per hectare.	Shainberg *et al.* 1990; Lentz and Sojka 1994
14.	Anionic PAM (spraying method)	Portneuf silt loam, clay loam, and silt loam	1.1%, 35%, and 45%	-	Mulch that is composed of fibers and other ingredients	Soil erosion was reduced 70% and increased infiltration 30%.	Trout *et al.* 1995; *Flanagan et al.* 2002
15.	Coconut fiber mat	Tropudult	9%	-	Preparation of mats to be spread on soil	Runoff and soil loss were reduced, and soil moisture increased	Mapa 1996

16.	Composted municipal solid wastes (CMSW)	Calcic Haploxeralf	5%	-	Direct spreading of the fibers on soil	Mulching with CMSW was beneficial in controlling runoff as it increased the absorption of water into the soil to 85%	Agassi *et al.* 1998
17.	Natural mulches: *Gossypium hirsutum* L., wood wastes-cotton fibers, *Piptadeniastrum africanum*-cotton fibers, peat-cellulose, jute fibers, (*Corchorus* spp.) treated with mineral oil, kenaf (*Hibiscus cannabinus* L.)- cotton, pine straw, and Bermuda grass (*Cynodon dactylon* (L.) Pers.) Natural/synthetic mulches: Cellulose fiber/ polypropylene, cellulose/ polypropylene/ polyethylene, cotton/ polyethylene, hemlock (*Tsuga* spp.)/polyester fiber, woven wood/ polypropylene, kraft paper sheet/fiber glass, kraft paper sheet/nylon, and embossed poplar (*Populus* spp.)/ polypropylene Synthetic mulches: Black polyethylene, polyester, polyethylene, and polypropylene	Beauregard silt loam	0% to 3%	-	Non-biological mulches	Synthetic mulches were more durable than natural or natural/synthetic mulches. Pine straw, cotton-polyethylene, woven wood-polypropylene, and synthetic/ cellulose mat had fair to good durability after three growing seasons.	Haywood 1999
18.	Straw, rice straw, straw/coconut, coconut, and aspen fibers (excelsior)	Sandy clay loam	60%	-	Mulch that is composed of fibers and other ingredients	The use of mulch reduced soil loss by 81% compared to bare soil.	McCullah and Howard 2000
19.	Organic wastes: Stabilized municipal waste (compost), unstabilized municipal waste, and sewage sludge	Xeric Torriorthent	15%	-	Mulch that is composed of fibers and other ingredients	Compost significantly reduced soil loss by 94% and runoff by 54% compared to other organic wastes.	Ros *et al.* 2001

20.	Coir/jute fiber treated with cationic softener				Preparation of mats to be spread on soil	The materials were non-polluting, renewable, and controlled erosion by re- establishment of vegetation.	Banerjee 2001
21.	Mulching mat comprised of non-woven geotextile, a jute net, and a geotextile mat	Decomposed granite soil	31°	-	Preparation of mats to be spread on soil	The materials stabilized the slope of granite soils and promoted the growth rate of plants.	Ahn *et al.* 2002
22.	Cellulose mulching and black polyethylene mulching method	Gleysol hydroamel-iorated	-	-	Mulch that is composed of fibers & other ingredients	Black polyethylene mulch reduced nitrogen leaching better than cellulose mulching due to its impermeability and durability.	Romic *et al.* 2003
22.	Black polyethylene mulching	Silt loam	-	-	Mulch that is composed of fibers & other ingredients		Green *et al.* 2003
23.	Coir geotextile	Sandy loam	26°	-	Preparation of mats to be spread on soil	Coir geotextile stimulated the growth of lemongrass and improved the organic carbon content, soil water content, soil moisture retention, and vegetative growth of the field area.	Lekha 2004
24.	PAM and phosphogypsum (PG)	Loamy sand, loam, and dark brown clay	15%	Interill	Mulch that is composed of fibers and other ingredients	The PAM mixed with PG reduced soil susceptibility to seal formation better than applying only PG on the soil.	Tang *et al.* 2006
25.	Elephant grass (*Pennisetum purpureum*)	Sandy loam, sandy clay loam, and loamy sand	6%, 9%, and 12%	-	Direct spreading of the fibers on soil	The highest cover of elephant grass increased the infiltration and reduced soil loss on sloping land.	Adekalu *et al.* 2007
26.	Wheat straw mulch	Sandy loam and silt loam	-	Splash	Direct spreading of the fibers on soil	Straw mulch decreased the mean splash loss 68% and increased the infiltration rate 54% compared to control soil. The treatment was more effective in sandy than in silt loam.	Kukal and Sarkar 2010

27.	Jute geotextile (JGT)	Silty-clay soil	-	Gullies	Preparation of mats to be spread on soil	- Prevented detachment of soil particles, which inhibited soil erosion by aiding vegetation growth on applied area; JGT reduced soil loss from 8.8 to 1.3 g mm^{-1}. Increased soil moisture content to 40% to 50%	Choudhury and Sanyal 2010
28.	PAM	Silty loam	25º	-	Mulch that is composed of fibers & other ingredients	Effectively reduced the erosion of steep sloping land	Li *et al.* 2011
29.	Rice straw mat/ PAM/ gypsum, rice straw mat/ sawdust/ PAM/gypsum, and rice straw mat/ chaff/ PAM/gypsum mulches	-	10% and 20%	-	Preparation of mats to be spread on soil	The rice straw mat/chaff/PAM/ gypsum reduced runoff greater than other mulches. Chaff and sawdust enhanced surface cover rate, infiltration, and delayed the time of initial runoff.	Lee *et al.* 2012
30.	Sweetgum (*Liquidambar styraciflua*) fruits, riprap, and sod	Silt loam	4.3%	Rills	Direct spreading of fibers on soil	Sod was the most effective method to control erosion followed by riprap and sweetgum balls according to the appearance of the rills.	Alqusaireen *et al.* 2013
31.	Rice straw mulch	Sandy loam soil	30%	Splash	Direct spreading of fibers on soil	Runoff commencement time was delayed and runoff volume, sediment concentration, sediment yield, soil loss, and splash erosion decreased.	Gholami *et al.* 2013
32.	Jute geotextiles	Peat soil & black cotton soil	-	-	Preparation of mats to be spread on soil	Jute geotextiles improved soil properties by increasing infiltration and strength of the soil.	Ghosh *et al.* 2014
33.	Barley straw mulch	Sandy loam	9%	Splash	Preparation of mats to be spread on soil	Straw mulch reduced splash erosion, soil sealing, runoff, and soil loss. It increased infiltration and drainage.	Gholami *et al.* 2014
34.	Rice straw blanket	-	-	-	Preparation of mats to be spread on soil	The rice straw blanket held soil particles, promoted vegetation growth, retained moisture, and prevented loss of N, P, and K in soil.	Deshmukh *et al.* 2015
35.	Straw mulch	Loamy sand	35%	-	Direct spreading of fibers on soil	Sixty percent mulch cover reduced approximately 70% of soil erosion in the first month after application.	Fernández and Vega 2016

Fernández and Vega (2013) found that straw mulch has a low decomposition rate and encourages rapid vegetation cover recovery better than wood-based mulch. Both types of mulching significantly reduced sediment yield and overland flow velocity, and they increased soil infiltration and vegetation cover (Robichaud *et al.* 2013).

Generally, past studies indicate that jute is the best candidate to prevent soil erosion due to its superior mechanical and hygroscopic properties relative to other cellulosic fibers. This statement is in agreement with Rickson (2003). Although jute fiber has a short life span, it is possible to delay its biodegradability by up to 20 y *via* different treatments and blending (Agrawal 2011). According to certain authors (*e.g.*, Gupta 1991) biodegradability is an advantage, as it allows the right amount of time for slopes to establish vegetation. In addition, the decomposition of jute fibers increases soil moisture content and enhances the nutrient contents in soil, which improves the ecological cycle of the applied area. Batra (1985) made a comparison between natural fibers such as jute, coir, and sisal. The water retention capacities of jute and sisal are better than that of coir. This is due to the high lignin content in coir, which decreases absorption because lignin is hydrophobic (Ghosh *et al.* 2009). The presence of lignin tends to inhibit microbial attack by keeping the fiber surface at low moisture levels (Ghosh *et al.* 2009). In this regard, the lignin properties in jute fibers exhibit high modulus, tenacity, and very low extension at break, whereas coir fiber exhibits the exact opposite qualities. Rickson (2003) reported that to prevent soil loss, the materials used must be lightweight, non-needle-punched, and woven to provide a conducive condition for vegetation growth where both light and space are available. However, researchers have confirmed that attained ground cover was more critical than the type of material. For instance, different mulches, such as wood strands (Foltz and Dooley 2003; Yanosek *et al.* 2006), pine needles (Pannkuk and Robichaud 2003; Smets *et al.* 2008), and wood shreds (Foltz and Copeland 2009), showed the same reduction of total soil loss with ground coverage of 70%. Table 2 summarizes the studies of soil erosion control using natural fibers in sequence.

POTENTIAL APPLICATION OF CELLULOSIC FIBRE FOR SOIL EROSION MITIGATION IN A BIOCOMPOSITE FORM

A material that incorporates two or more different polymers with at least one component that is bio-based or biodegradable is called a biocomposite. It consists of a matrix that acts as a binder material and dominant natural fibers, acting as a “back-bone” of the biocomposite. However, in the context of this review, the term “biocomposite” will refer to a mixture or blended cellulosic fiber material that is not perceived as a conventional biocomposite description in which fiber acts as reinforcement within a matrix. Most often, the matrix is made from polymers derived from renewable and non-renewable resources and is commonly degradable. The main purpose of the matrix is to transfer the load or stress exerted on the biocomposite to the reinforcement material and protect it from adverse environmental effects. In contrast, the reinforcement’s role is to provide mechanical support for the biocomposite, which is why this material commonly consists of either fibers or particles.

In some cases, a compatibilizer is added to enhance the adhesive interaction between matrix and fiber, as the compatibility of materials in a composite is vital in determining the properties and strength of the composite (Barton *et al.* 2014). Depending on the purpose and type of the biocomposite, the structure can be produced by various methods, including machine press, extrusion, injection molding, compression molding, resin transfer molding, and hand layout methods. Biocomposites that have been used to control soil erosion are shown in Table 2. From 2008 until 2012, Restoration Technologies (RT) group, based in the United States, worked on a wood chip composite material (chipped woody biomass and an inorganic cement binder) called Zerosion to create an erosion control material that stabilizes soil quickly and possesses superior mechanical properties to withstand adverse natural impacts and degrade after more than five years after application. Because current erosion control products have low endurance towards the climate, Zerosion was created to have high durability, while at the same time being permeable to water and enhancing vegetation growth. However, there has yet to be a progress report or publication on the development of this material.

Maghchiche *et al.* (2010) conducted a study to determine the effects of different synthetic polymers and biopolymers at low concentrations (0.03% to 1%) in arid and semi-arid soils in North Africa. The cellulose was derived from the alfalfa plant and blended with a poly(acrylamide) (PAM) solution. Different concentrations of cellulose (0 mg/L to 20 mg/L) and PAM (0 g/ L to 0.5 g/ L) were prepared. They found that the polymer composites (10 mg/L polyacrylamide and 0.5 g/L cellulose) in soil improved the soil’s physical properties and augmented water retention by 60% in arid soils compared with the application of any other polymer at the same concentration. Snidjer (2010) applied GreenGran (natural fiber/PLA/PHB) granules, which have superior technical properties to previous natural fibers and are comparable to other glass fiber reinforced plastics, onto riverbanks. GreenGran (natural fiber/PLA/PHB) granules are environmentally friendly (they will decompose after a certain period) and can be reused up to seven times. There has been much research interest in soil erosion to find new technologies/materials with which to stabilise soil slopes. Many geosynthetic materials have been developed to stabilise soil slopes; however the integration of biodegradable material utilization that environmentally friendly is timely (Ngo *et al.* 2019).

The studies shown in Tables 2 and 3 indicate that the research on the application of biocomposites in soil erosion mitigation is limited compared to that on the application of natural fibers. This could be due to poor accessibility and high cost of biodegradable polymers (Sahari and Sapuan 2011) relative to natural fibers, which are abundant and inexpensive (Sapuan and Maleque 2005), have low density, and lack remnants upon incineration (Wollerdorfer and Bader 1998; Leman *et al.* 2008; Zainudin *et al.* 2009). Furthermore, instead of focusing on the creation of new products from renewable resources, most of the erosion control measures are focused on mechanical structures (*e.g.*, construction of terraces, silt pits, waterways, and gabions) (Mati 2012), cover crops, and mulching as the easiest way to control soil loss (Hartemink 2006). Poor interactions between the matrix and natural fibers due to its hydrophilic nature of fibers, which reduces impact strength (Faruk *et al.* 2014), is another factor that limits the evolution of biocomposites.

Chemical modification, such as alkaline treatment, is a common technique used to improve the compatibility of matrices with natural fiber reinforced polymers (Bledzki *et al.* 2012). In addition, the application of biocomposites for outdoor applications is not economical due to the large price fluctuations and variable quality of fiber, and it is susceptible to adverse environmental impacts (fungus attack, weathering, *etc.*) (Faruk *et al.* 2014).

Table 3. Biocomposite Materials in Controlling Soil Erosion

No.	Type of Composites	Composite Form/ Method Applied	Type of Soil/Location	Slope Steepness	Type of Erosion	Results	References
1.	Polyacrylamide (synthetic plastic compounds)/cellulose composite	Liquid/spraying	Arid and semiarid soil	-	-	Improved physical properties of soil and reduced water losses from evaporation	Maghchiche *et al.* 2010
2.	Natural fiber/polylactic acid (PLA)/ Polyhydroxybutyrate (PHB) composite	Blocks made from granules/scattering	Riverbank and dams	-	-	Blocks made from GreenGran granules protected the riverbanks and dams from erosion	Snidjer 2010

The type of species, ecological factors, and postharvest handling methods are some of the main factors that affect the quality of natural fibers (Faruk *et al.* 2014). However, the major drawback of natural fiber is that its mechanical properties depend on its climate, growing conditions, processing technique, and water absorption. Most of the studies involving biocomposites were in the automotive (Oksman *et al.* 2003; Kim *et al.* 2011; Faruk *et al.* 2014), packaging (Bastioli 1998), wood (Fuad *et al.* 1994; Izani *et al.* 2013; Ibrahim *et al.* 2014), household furniture (Sapuan and Maleque 2005), and construction applications (Burgueño *et al.* 2004; Singh *et al.* 2010). Several studies (Wollerdorfer and Bader 1998; Avérous and Boquillon 2004; Soykeabkaew *et al.* 2004; Ma *et al.* 2005; Tserki *et al.* 2006; Dittenber and Gangarao 2012; Nagarajan *et al.* 2013) reported that a biodegradable matrix reinforced with natural fibers enhanced the mechanical properties (*e.g.*, tensile strength, flexural strength, and specific modulus) and the biodegradation rate of composites, and they formed lightweight and eco-friendly composites.

POTENTIAL MATRICES IN BIOCOMPOSITES FROM NATURAL RESOURCES

Recently, biocomposites consisting of natural fiber and bio-matrices, such as reinforcement material and binders, respectively, have been developed. Bio-matrices are polymer matrices that contain bio-based products, such as starch, cellulose, polylactide, and polhydroxy-alkanoate (PHAs). Matrices made from natural resources are difficult to produce. Despite the abundance of these materials in nature, they are often modified and require processing before being incorporated into biocomposite materials (Toriz *et al.* 2003).

Sludge

Sludge in general can be defined as a remaining semi-solid material that is produced as a by-product from industry, water treatment, or wastewater treatment processes. In the U.S., pulp and paper factories produce 4 million dry tons of sludge for each 80 million tons of pulp production per year (Miner and Unwin 1991). The situation is similar for municipal wastewater sludge, where formerly most of the sludge was disposed of by landfilling, ocean dumping, and spreading on the land, which causes various environmental problems. Thus, it is crucial to find different methods for managing sludge waste. To date, there have been few studies on using sludge as a matrix in composites. Instead, many researchers have applied it in cementitious and reinforced materials. Tay (1987) produced bricks for construction and building by mixing wastewater sludge with clay.

Comparisons between the effects of dried sludge and ash sludge on the properties of bricks have been performed. For ash sludge, the sludge was first burned at over 600 °C in a furnace to eliminate organic matter before it was mixed with clay at 10 wt%, 20 wt%, 30 wt%, 40 wt%, and 50 wt%, whereas for dried sludge, it was mixed with clay at 10 wt%, 20 wt%, 30 wt%, and 40 wt%. Both samples were then fed into an extrusion machine. The suitable percentage of sludge should not exceed more than 40 wt% and 50 wt% for dried and ash sludge, respectively, as increasing the percentage of sludge causes an uneven brick surface. Results indicated that the hydrophilicity of bricks increased as sludge percentage increased, which is unfavorable in the building industry as it decreases the robustness of the bricks. A high percentage of sludge also decreased the compressive strength of the bricks, which was in agreement with Nair *et al.* (2013). In addition, ash sludge bricks have better durability than dried sludge bricks. However, the mixture of sludge and clay may not be suitable to be used as a construction material due to the poor surface texture of the bricks produced.

Son *et al.* (2001) investigated the physical and mechanical properties of paper sludge-thermoplastic polymer composites based on the sludge's particle size and the extrusion temperature exerted on them. In the study, paper sludge, which acts as a reinforcing filler material, was blended with thermoplastic polymers before being introduced into a single-screw extruder and then prepared with an injection-molding machine at 200 °C. Results showed that swelling thickness, water absorption, tensile strength, and flexural strength were improved with smaller sludge particle sizes. This was because smaller particle sizes of sludge, which are mostly comprised of inorganic materials, have higher porosity than larger particle sizes, which enhances water absorption capacity. Further, smaller particle sizes fill up the void spaces in composites, which leads to superior mechanical strength. However, both variables (particle size and temperature) had no effect on the unnotched impact strength test.

In contrast, increasing extrusion temperature had a positive impact on all tests conducted (thickness swelling, water absorption, tensile, flexural, and impact strengths) due to better wettability between the polymer and paper sludge fibers. However, for notched and unnotched impact strength, the impact strengths slightly decreased with an increase in temperature of 230 to 250 °C, which was probably due to thermal decomposition of the composite that caused a failure in effective interfacial adhesion between cellulose and matrix. Overall, paper sludge from industrial waste has a high potential to replace the existing reinforcement filler in thermoplastic polymers (Elloumi *et al.* 2016). Ingunza *et al.* (2015) incorporated sewage sludge (at concentrations of 2%, 4%, 6%, 8%, and 10% dry mass) with clay to produce ceramic roof tiles. Water absorption increased with the addition of sludge into the clay. This occurred due to the high content of organic matter (71%) in the sludge, which caused higher porosity and led to lower mechanical properties of the ceramic roof tiles, as the flexural rupture strength decreased with the augmentation of sludge dosage (Androff *et al*. 1997). This is the main drawback of using sludge for construction materials. The amount of sludge recommended by Ingunza *et al.* (2015) in ceramic mass used to manufacture roof tiles was 4% of dry weight sludge. However, Kutuk and Oguz (2016) found that the tensile strength of their studied composite increased when the content of sewage sludge ash particles was increased to 20%, which was then followed by a decrease in tensile strength when the sewage sludge ash particle content was increased beyond 20%. Similarly, the impact strength of the composites increased when the content of sewage sludge ash particles was increased to 10%, and it remained constant at 25% to 40% sludge ash content.

Using the solution casting technique, Purohit and Satapathy (2017) fabricated composites consisting of epoxy as a matrix, and Linz-Donawitz (LD) wastes (generated from iron and steel industries sludge) functioned as a filler with various weight proportions (0, 5, 10, 15, and 20 wt%). The mechanical properties of the composites were then compared with epoxy-based composites of blast furnace (BF) slag and LD slug from previous studies. The results revealed that epoxy-LD sludge composites exhibit superior mechanical and wear characteristics to epoxy-BF slag and epoxy-LD slug composites. However, the increase of filler loading in composites decreased the tensile strength, increased the flexural strength, and improved the micro-hardness values of epoxy-LD sludge composites. The reduction of tensile strength was mainly due to the inefficient load stress transfer between LD sludge particles and the matrix. The authors concluded that there is potential to produce composites from sludge waste and epoxy matrix with the solution casting technique.

Polylactide

Polylactide or polylactid acid is derived from renewable agricultural raw resources, such as corn starch, tapioca roots, chips, starch, or sugarcane, which are then fermented to lactic acid. It is commonly used in decomposable packaging material and medical implants due to its biodegradability. Depending on the size and type of production, PLA typically takes only a few years to decompose compared to petroleum-based products, which take hundreds to thousands of years to degrade. The decomposition of PLA occurs via the breakdown of compounds by water to lactic acid with the aid of microbes to produce water and carbon dioxide (Oksman *et al.* 2003). In the future, PLA, which is a by-product, could possibly turn into a carbon sink and contribute to the reduction of greenhouse gases (Dittenber and Gangarao 2012). Oksman *et al.* (2003) compared the mechanical properties of PLA/flax composite with polypropylene flax fiber composite (PP/flax). They found that the PLA/flax composite had a tensile strength and tensile modulus of 32 MPa and 2.1 GPa higher, respectively, than the PP/flax composite. This means that PLA works well as a matrix with a 50% improvement in mechanical properties relative to PP, which has been used widely in many industries. This shows the potential of PLA to replace conventional thermoplastic composites as a matrix in natural fiber composites. However, the interfacial adhesion of matrix-fiber should be considered, as it determines the strength of the composite. Ochi (2008) investigated the tensile and flexural strength of unidirectional biocomposites that were fabricated from kenaf fiber and PLA resin at a molding temperature of 160 ºC, as kenaf fiber’s tensile strength will decrease if the temperature exceeds 180 ºC. With 70% fiber loading, the biocomposite demonstrated high tensile and flexural strengths of 223 and 254 MPa, respectively. The kenaf/PLA composites decreased in weight drastically to 38% after four weeks of evaluation using a garbage-processing machine, which indicates that it is fully biodegradable, as it only releases water and carbon dioxide during the degradation process.

Thermoplastic Starch

Starch is derived from polysaccharides of wheat, maize, potato, rice, tapioca, and other plants. In the early 1970s, starch was used to produce biodegradable plastics (Curvelo *et al.* 2001), which then precipitated the evolution of starch. Starch can be processed into 649 thermoplastic starch (TPS) under the action of high temperature and shear forces (Shogren 1992; Forssell *et al.* 1997). The application of TPS as a matrix in biocomposites has been reported by Hermann *et al.* (1998) and Bastioli (1998) to be one of the main polymers being extensively studied today by other researchers. Thermoplastic starch has two main drawbacks in that it is water-soluble and has poor mechanical properties (Curvelo *et al.* 2001). Therefore, TPS that is commonly used in packaging and agricultural applications is blended with other polymers, such as natural fiber in contents that usually exceed 50% to improve the properties of composites. It is favorable for its renewable, biodegradable, abundant, and low-cost polymer characteristics. Curvelo *et al.* (2001) prepared biocomposites comprised of TPS and cellulosic fiber from the pulp of *Eucalyptus urograndis*. Both polymers were mixed at 170 °C and hot pressed before cutting to a specific size prior to mechanical tests.

Evaluation of the tensile strength showed a 100% increase, whereas modulus increased more than 50% compared to non-reinforced TPS. A strong adhesive interaction between TPS and cellulose fiber was achieved with 16% fiber content, as the fiber was homogenously dispersed. The absence of fiber pullout on the surface of the composite due to perfect starch coverage indicated a good adhesion between matrix and fiber (Salilba and Snide 1990). However, water sorption was reduced sharply with the incorporation of fiber. Ma *et al.* (2005) produced TPS composites by mixing micro winceyette fiber into a matrix derived from urea/formamide-plasticized corn starch before introducing it into a single screw extruder under four heating zones of 120, 130, 130, and 110 °C. The tensile strength, water resistance, and thermal stability of the composite were significantly improved due to good adhesion between the starch and fiber. The results demonstrated that, as fiber content increased from 0% to 20%, tensile strength increased to 15.16 MPa, and elongation were reduced from 105% to 19%.

Further, the addition of water to the contents of the composites decreased its mechanical properties, whereas the introduction of fiber effectively prevented water absorption by the TPS matrix and reduced the water sensitivity of TPS. Torres *et al.* (2007) studied TPS composites reinforced with sisal, jute, and cabuya with a matrix of potato, sweet potato, and corn starch with a compression molding press to compact the composite at temperatures of 130, 150, and 175 °C. In this study, ethylene glycol, glycerol, propylene glycol, and chitosan were used as plasticizers. The tensile strength exhibited a great improvement of almost 100% in potato starch/sisal composite, whereas jute and cabuya fiber showed improvements in tensile strength of 54 and 15%, respectively. When compared with the unreinforced matrix, the impact strengths of potato starch reinforced with jute and cabuya fibers displayed extraordinary improvements of approximately 100% and 200%, respectively. Ethylene glycol and glycerol showed better tensile strength compared to the plasticizers used in the study. All plasticizers showed similar results for impact strength except for water, which showed an improvement of up to 35% compared to propylene glycol and chitosan. Generally, TPS and natural fibers are highly compatible in composites (Avérous and Halley 2009).

SOIL STABILIZER IN OIL PALM PLANTATIONS

Organic mulches using OPEFB are one of common methods that have been practiced over several decades in oil palm plantations to prevent soil degradation, hence sustaining long-term productivity (Afandi *et al.* 2017). However, due to it bulky size, the application of OPEFB is limited to matured palm oil areas only. This brought to new opportunity for an innovative OPEFB (and other potential matrix such as sludge) based biocomposite (in a pellet form) to be applied in other areas that are more vulnerable to erosion (Ashikin *et al.* 2019). The replanting of oil palm will be performed after 25 to 30 years of economic life span of oil palm trees. An oil palm tree starts to mature at 3 years to 4 years after it has been planted. Therefore, the environment, particularly the water bodies, are vulnerable to erosion due to the absence of vegetation cover. Full vegetation cover has lower soil loss than bare soil, as the roots hold soil particles together and reduce raindrop impact (Sahat *et al.* 2016). Land preparation is the most critical element of oil palm plantations, as erosion and sedimentation occur at an alarming rate during land preparation (PORIM 1994; Ismail 1997).

Exposed soil surfaces accelerate erosion rates, especially during frequent rainfall, which causes significant overland flow that deteriorate the surface water quality (Nor Ashikin *et al.* (2019). The erosion rate depends on slope steepness and prevention measures taken (Sahat *et al.* 2016). Heavy machinery and tracked vehicles often worsen the situation *via* soil compaction, which leads to deterioration in soil structure and fertility. In addition, the compaction of soil decreases soil porosity, which reduces infiltration rates. Compacted path surfaces caused by heavy machinery may increase the potential for Horton Overland Flow (HOF) (Ziegler *et al.* 2001), which leads to soil erosion due to water runoff. Soil erosion tends to happen in mature palm oil plantations because cover crops usually disappear at this stage (Hartemink 2006). Exposed and compacted soil thus intensify run-off and soil erosion Therefore, as soil erosion in oil palm plantations significantly impacts soil health, preventive measures for mitigating soil erosion have been taken for decades. Some of the mitigation measures that have been implemented include early cover crop cultivation, placement of dry prune fronds and old palm trunks along harvesting paths, construction of silt pits, and empty fruit bunch mulching (Palm Oil Research Institute of Malaysia 1994). Clay (2004) proposed that before planting, careful consideration must be given to certain factors, such as soil type and slope of plantation area, as some soils are not suitable for oil palm plantations and may cause adverse impacts in the future.

Principles of Soil Stabilizer

In the Tenth Malaysia Plan (2011 to 2015), the Malaysian government recognized the importance of environmental sustainability as part of a comprehensive socio-economic development plan, whereby issues, such as climate change, environmental degradation, and sustainable utilization of Malaysia's natural endowment, were addressed. In the Eleventh Malaysia Plan (2016 to 2020), green growth was a fundamental shift in how Malaysia sees the role of natural resources and the environment in its socio-economic development, simultaneously protecting both development gains and biodiversity. Therefore, mitigation of natural hazards, such as floods, has been given serious attention by the Malaysian government in the Eleventh Malaysia Plan, in which innovative solutions through the development of green technology are emphasized and consider the preservation and optimization of land use and the intensity of extreme weather regimes. This represents a continuous commitment of the Malaysian government to sustainability inspired by the National Environmental Policy (2002).

There are many related studies on soil stabilization using chemical agents, such as cementitious and pozzolanic materials (Por *et al.* 2015, 2017; Chomporat 2019). However, in this review the term "soil stabilizer" refers to reapplication of bio-based resources, especially byproducts from agricultural wastes, back into the soil to stabilize the soil structure. This is achieved by preventing or reducing the impact of raindrops on bare soil surfaces, which typically cause erosion if preventive measures are not taken. Soil erosion can be divided into four primary processes, which are splash erosion, sheet erosion, rill erosion, and gully erosion. Splash erosion is the first and least severe stage in the soil erosion process, followed by sheet erosion, rill erosion, and finally gully erosion, which is the most severe stage. In splash erosion, when raindrops strike bare soil, soil particles disintegrate and disaggregate into fine particles, consequently thrown up to one meter, clog up soil pores, and create a surface seal, which impedes the permeability of water into soil, thus increasing runoff. If no preventive steps are taken to mitigate the first process, then sheet erosion will occur.

Sheet erosion involves the removal of the thin layer of topsoil that comprises most of the nutrients and organic matter in soil. Soil erosion is a gradual process and is often unnoticed. However, it can accelerate to an alarming rate and cause a severe loss of topsoil.

Soil erosion on steep hillslopes can rapidly evolve from splash or sheet erosion to rill erosion when there is sufficient extra rainfall energy exerted on the soil or if sufficient overland flow occurs (Di Stefano *et al.* 2013). Rill erosion is the intermediate stage between splash and gully erosion (Jackson 1997). Rills are small channels created by water runoff with a depth of less than 0.3 m. They are commonly seen in cultivated fields and can cause extensive soil losses (Govers and Poesen 1988; Miao *et al.* 2011), especially during the development of rill networks, as they are significantly affected by rainfall intensity (Shen *et al.* 2015). Gully erosion is the stage following rill erosion. Gully erosion can be formed by runoff water concentration or by gradual deepening of rills in which the channel depth reaches 2 to 3 m (Zachar 1982). Normally, this type of erosion is clearly noticeable, as it affects soil productivity and damages roads and buildings (Department of Natural 806 Resources and Water 2006).

Therefore, preventive measures should be taken at the early stages of sheet or rill erosion so that severe soil structure damage can be stopped. This is because, during the first stage (splash erosion), the erosion event occurs without an obvious indication; thus, soil stabilization cannot typically be employed effectively. During gully erosion, the application of soil stabilizer seems to be less effective due to the worsening of soil condition. Meyer *et al.* (1970) added that mulches are generally ineffective once rills form. Therefore, another soil protection strategy needs to be applied to impede the formation of gullies.

Application of "Green" Resources as Soil Stabilizers in Oil Palm Plantations

Various strategies have been implemented to stabilize soil structure, including mechanical, physical, and chemical reaction techniques. Soil reinforcement, soil replacement, compaction, and chemical soil stabilization are some of the techniques used to enhance the mechanical properties of soil (Tabatabaee 1985). In oil palm plantations, terracing hills and silt pits that trap water sediments from surface runoff, stacking fronds used to minimize runoff velocity, and leguminous cover crop that helps in restocking soil organic matter content are some of the common practices reported by Mohsen *et al.* (2014). In this section, the efficiency of controlling soil erosion by using natural resources, such as EFB, oil palm frond, eco-mat, and leguminous cover crop plants, are discussed.

OPEFB mulch

The introduction of the Malaysian Environmental Air Quality Regulation in 1978 triggered changes in EFB disposal management methods, as EFB was traditionally incinerated due to its wet and bulky properties (Abu Bakar *et al.* 2011). Mulches originating from fibrous byproducts, such as EFB and fruit mesocarp fibers, are also used as a soil conservation method in oil palm plantations (Basiron 2007). In the oil palm industry, byproducts, such as EFB, are among the most favored natural mulches because they reduce soil erosion and runoff (Lim and Messchalck 1979) and release carbon and other beneficial nutrients during the decomposition process, thus improving soil fertility (Wagner and Wolf 1998). Lord and Clay (2006) suggested the utilization of EFB with palm oil mill effluent (POME) or palm kernel cake as compost materials in nursery bags, as seedling nurseries usually involve the stripping of topsoil, which deteriorates the soil structure. Empty fruit branch ameliorates the soil structure by providing better aeration, increasing water retention, and reducing soil acidity (Hoong and Nadarajah 1988; Abdullah and Sulaiman 2013).

In addition, empty fruit bunch increases the pH and aggregate stability of soil more effectively than other treatment methods, such as eco-mats (Ping *et al.* 2012). Beyond maintaining the soil structure, EFB is a beneficial nutritional source for organic fertilizers and soil conditioning agents, as it contains high nutrient concentrations and releases them gradually into the soil via microbes, thus increasing ecological recycling efficiency (Abdullah and Sulaiman 2013; Mohsen *et al.* 2014). Studies have shown that EFB-treated soil showed significant increases in total N and C, and exchangeable K, Ca, and Mg (Hamdan *et al.* 1998). According to Singh *et al.* (1999), 1000 kg of EFB has an amount of nutrients comparable with 7.0 kg of urea, 2.8 kg of phosphate, 19.3 kg of rock, and 4.4 kg of muriate of potash and kieserite, which indicates that this byproduct consists of many minerals and nutrients needed by soil, thus increasing the growth rate of vegetation and reducing soil erosion (Singh *et al.* 1981).

Although EFB mulching enhances soil nutrient and soil water content, a drawback of EFB is that it decomposes quickly. Often, it becomes ineffective in conserving soil and water approximately 8 months after its application (Khalid and Tarmizi 2008); therefore, re-mulching is required after 6 to 7 months to maintain soil moisture conservation efficiency (Arif *et al.* 2003). However, Moradi *et al.* (2012) and Ping *et al.* (2012) reported that mulching materials, such as EFB, require 12 months to decompose and improve soil chemical and physical properties synchronously. Due to all of the advantages mentioned above, Abu Bakar *et al.* (2011), Moradi *et al.* (2012), and Ping *et al.* (2012) concurred that EFB application is the best practice to preserve soil particles from erosion by improving soil aggregate stability due to its high organic matter content. Pruned oil palm fronds are another form of oil palm waste that is typically used to protect surface soil from direct raindrop impact. Lord and Clay (2006) recommended the application of fronds in mitigating sheet and rill erosion to reduce soil loss and assist in the establishment of natural vegetation. Normally, 24 fronds are stacked together for an oil palm tree (Sulaiman *et al.* 2012).

This method has been demonstrated by Mohd Ali (1997) to enhance organic matter, aggregate stability, and water content in soil, and decrease soil bulk density. The total organic matter in soil is critical in determining the stability of soil aggregates, as the loss of organic matter results in unstable soil structure (Oades 1988). However, Moradi *et al.* (2012) and Sahat *et al.* (2016) found that dried fronds are less effectives in reducing soil erosion rates than other cover crops, such as grass. However, oil palm fronds can be used to slow down surface runoff velocity by acting as surface flow breakers. In addition, Lim (1990) found that pruned fronds can decrease erosion rates on slopes of 3º to 5º by averting the direct impact of rain drops. The adjustment of the layout position of dried fronds also needs to be considered, as a layout position perpendicular to groundwater surface flows is more effective in preventing soil loss compared to a layout position parallel to groundwater surface flows (Sahat *et al.* 2016). Even though pruned fronds release high amounts of nutrients, such as N, P, K, and Mg, into soil (Husin *et al.* 1987), they are a less practical solution to reduce soil loss and enhance soil water content to reduce soil loss and enhance soil water content than other management practices in non-terraced oil palm plantations (Moradi *et al.* 2012). Moradi *et al.* (2012) found that oil palm fronds had significantly lower K and Mg but higher C, N, and Ca concentrations than EFB.

Frond pruning

Pruned oil palm fronds are another form of oil palm waste that is typically used to protect surface soil from direct raindrop impact. Lord and Clay (2006) recommended the application of fronds in mitigating sheet and rill erosion to reduce soil loss and assist in the establishment of natural vegetation. This method has been shown by Mohd Ali (1997) to enhance organic matter, aggregate stability and water content in soil, and decrease soil bulk density. The total organic matter in soil is critical in determining the stability of soil aggregates, as the loss of organic matter results in unstable soil structure (Oades 1988). However, Moradi *et al.* (2012) and Sahat *et al.* (2016) found that dried fronds are less effective in reducing soil erosion rates than other cover crops, such as grass.

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Eco-mats

Eco-mats are a recent development using EFB in response to the difficulties in handling this fiber. Eco-mats are a compaction of EFB in the form of a carpet-like material (Yeo 2007) with no chemicals added (Khalid and Tarmizi 2008). Eco-mats are easy to manage, environmentally friendly, and less expensive than EFB mulch (Mohsen *et al.* 2014). They have been demonstrated to improve the organic matter content, nutrient contents, moisture holding capacity, and structure of soil, and they prevent erosion on slopes (Khalid and Tarmizi 2008). Organic matter stabilizes soil structure by acting as a binding agent that combines mineral particles and creates stable soil aggregates (Tisdall and Oades 1982).

Eco-mats fortify the structure of soil and impede it from erosion, thus creating more favorable circumstances for root growth than bare soil (Khalid and Tarmizi 2008). Ibrahim (2006) discovered that beyond accelerating cover crop growth rate, eco-mats contain N, P, K, C, Mg, and Ca (MPOB 2003; Khalid and Tarmizi 2008). However, Moradi *et al.* (2012) claimed that eco-mats are not recommended because although they increased bulk density compared to EFB and palm frond, which was probably due to the manufacturing process, eco-mats contain lower nutrient concentrations, water content, porosity, and saturated hydraulic conductivity.

Leguminous cover plants

Leguminous cover crops, which are established in the inter-row areas of oil palm trees to deter soil erosion (especially in slope areas) are commonly sown during the first 240 to 300 days of land clearing (Wahab 2001; Turner and Gillbanks 2003). Legume cover crops, such as *Mucuna bracteata*, *Calopogonium mucunoides*, *Axonopus compressus*, and *Pueraria phaseoloides*, are cultivated to cover and shield the soil from weeds or plants. *M. bracteata* is a fast-growing plant that grows about 10 cm to 15 cm per day and is suitable for soil conservation purposes, as it has been proven to decrease soil loss and retain soil moisture better than other surface types, such as bare soil, half grass cover, and half dry frond (Sahat *et al.* 2016). *A. compressus* was reported to grow faster than *M. bracteata*, which took 6 months to provide a dense vegetative growth, whereas *A. compressus* provides such vegetative growth within 3 months, making it the most suitable cover crop candidate for oil palm plantations (Samedani *et al.* 2015).

Beyond the advantageous effects of legume cover on maintaining soil structure, the physical and chemical characteristics of soil and soil fertility are also improved (Watson *et al.* 2002). Through reducing erosion and runoff, cover crops prevent water resources from being contaminated by nonpoint source pollution caused by the washing off of sediments (Clark 2010). Permanent cover crops reduce erosion risk and consequently maintain soil nutrient and organic matter content, and they improve soil structure (Lal *et al.* 1991). Khalid *et al.* (2000) performed a comparison study between legumes, weeds, and litter (mixture of legumes and weeds) in an 18-month-old oil palm area and discovered that legumes contribute a relatively high amount of total nutrients (*e.g.*, N, P, K, Ca, and Mg) in soil. This was in agreement with Szott (1987) and Lehmann *et al.* (2000). However, nutrient competition between cover crops and oil palm trees may occur, which reduces palm oil production. If climber legumes are used as a cover crop, comprehensive plant nursery management is needed to prevent them from smothering the tree crops (Watson 1989; Samedani *et al.* 2015).

Limitations of "Green" Resources in Soil Stabilizer

Although natural polymers have enormous advantages regarding environmental issues, there are some limitations to dealing with these polymers. The main concern in using natural fibers to reinforce soil is the loss of tensile strength with time, which is usually due to physical, biological, or chemical effects or their combined action (Kugan and Sarsby 2011). In addition, unlike synthetic polymers, the mechanical properties of vegetable fibers tend to change based on various factors, such as source, age, species, chemical constituents, and internal structure (Satyanarayana *et al.* 1986).

EFB-SEAWEED COMPOSITE IN SOIL STABILIZER APPLICATIONS

Fundamentally, vegetation plays a significant role in the natural mitigation of soil erosion. However, human alteration (land clearing) and environmental consequences (climate change) have had tremendous impacts on geomorphological process and accelerated soil erosion, which results in sedimentation. Sedimentation increases the vulnerability of watersheds to natural flood disasters (Lee *et al.* 2012; Syakir *et al.* 2016; Zafirah *et al.* 2016). Therefore, natural fibers are a promising biomaterial in mitigating soil erosion due to their potential role in promoting water circulation within the soil profile (Guerra *et al.* 2015). The fundamental mechanisms of fiber-soil interaction are critical in understanding the infiltration capacity of a particular degraded soil system.

Interaction of Soil and EFB-seaweed Composite

Flood initiation phenomena are presented in Fig. 1. The roles of EFB-seaweed composites in reducing the impacts of raindrops during the sheet or rill erosion stage are also illustrated in Fig. 1. Bare soil (at the right side of Fig. 1) is exposed to the impact of rain drops, which causes soil particles to disintegrate and disaggregate into fine particles. The absence of organic matter and exchangeable cations worsens the situation, as the loss of both are closely related to decreased soil aggregate stability (Oades 1988). The soil particle disintegration process weakens the interparticle attractive force, which deteriorates the soil structure. The disaggregation mechanism causes fine particles to spread out in all directions up to a distance of 1 m, clogging the soil pores. These clogged pores create a surface seal, which increases soil impermeability and consequently impedes the infiltration of water into the soil system. This results in a high volume of surface run off and soil erosion.

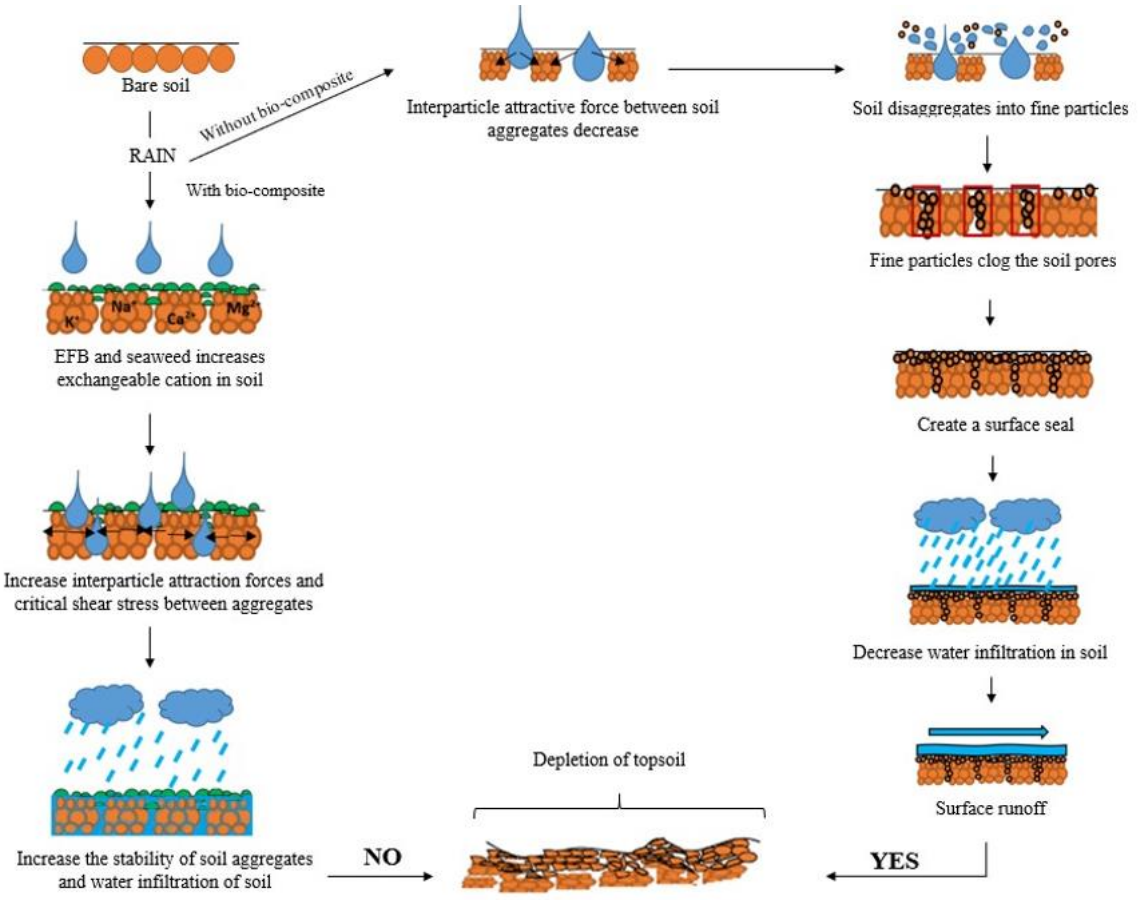

Fig. 1. The role of biodegradable materials in controlling soil erosion

In contrast, bare soil covered with RBP (OPEFB-seaweed) (shown on the left side of Fig. 1) increases the interparticle attraction force between soil particles. The presence of ions in seaweed contributes to the increase of exchangeable cations in soil, thus improving the soil structure and soil fertility. Increasing the organic matter and exchangeable cations in the soil improves the stability of soil, as they act as a binding agent that enhances the stability of aggregates (Tisdall and Oades 1982; Haynes *et al.* 1991; Shepherd *et al.* 2001). The increase of interparticle attraction forces increases the critical shear stress between soil particles, which makes it difficult for raindrops to break these particles and disaggregate them into fine particles. This increases the infiltration of water into soil and reduces surface run off and soil erosion.

Understanding the mechanism of the interaction between the biodegradable composite with the degraded soil system is critical in increasing soil infiltration capacity. Stable interparticle attraction increases the critical shear stress between soil particles, which results in high resistance of the soil system to raindrop impacts, thus reducing surface runoff and soil erosion. Further, the selected matrix (seaweed) has a high ion content, which complements the binding properties of the composite and improves soil fertility (Nurin *et al.* 2016). Such an understanding provides allows the implementation of prevention measures at early states of erosion (*i.e.*, the development of sheet-type erosion), thus lowering the risks of natural hazards.

Importance of EFB-seaweed Composite as a Soil Stabilizer

The hydrophilic characteristics of biodegradable materials demonstrate high potential in absorbing raindrop impacts and retaining water, and they subsequently release the water into the soil as the material gradually degrades after a certain time period (Syakir *et al.* 2016). Such a mechanism stabilizes the degraded soil system, which improves its water circulation process. Remarkably, the unique hydrophilic characteristics of these natural fibers plays a significant role in absorbing raindrop impacts and retaining and releasing the water in a gradual fashion upon degradation (Syakir *et al.* 2016).

Unlike other erosion control materials, such as mulches and geotextiles, which need to be applied manually onto the soil, the pellet-shaped EFB-seaweed composite does not fully rely on manual labor. Instead, machines, such as tractor fertilizer spreaders, can be used to disperse this biocomposite onto potential areas. At the decomposition phase, natural fibers that contain distinctive nutrients (Nurin *et al.* 2016) are essential for soil fertility and plant growth (Syakir *et al.* 2016). In this case, seaweed is an option for the matrix (Nurin *et al.* 2016) and is part of the biocomposite-soil interaction mechanism studies due to its beneficial element content, which is essential for soil fertility and plant growth.

Challenges and Limitations of EFB-seaweed as a Soil Stabilizer

Although EFB-seaweed composites have high potential for reducing soil run-off and improving the water circulation system, there are some limitations and challenges for the application of this biocomposite. Firstly, the proportions of EFB and seaweed in the composite have yet to be determined. This factor plays a vital role in defining the mechanical properties of a biocomposite. Incorrect proportions can lead to micro cracks on the surface of the composite, thus affecting its performance during application. Secondly, the EFB-seaweed composite seems to be limited for application on areas with less than 25° slope. At the early stage of studying this composite, attention was only given to the physical and mechanical characteristics of the EFB-seaweed composite (water absorption, impact strength, *etc.*). In addition, “anchor” behavior was considered to ensure that the biocomposite could be rooted to the ground during application.

Future Perspective

The application of abundance natural fiber from agriculture waste in composites has great potential for use as a soil stabilizer due its natural hydrophilic characteristics. Such green composites can be developed at lower cost by blending the matrix with abundant materials, such sludge, polylactide and thermo plastic starch. This review was inspired by the exploration of new waste management initiatives, which can be potentially mobilized by the leading agriculture companies to restore degraded soil systems in plantation areas. Such optimization of waste resources will also benefit the economy of the agricultural industry in the long run.

The capacity of the studied biocomposite to retain significant amounts of water and increase water circulation in the soil system is critical to the improvement of soil fertility and productivity, particularly in plantation areas. Its special characteristics are promising for cost effective and sustainable management of plantations, especially in tropical regions that are subjected to an abundance of rainfall. In addition, such an understanding will open new perspectives of waste recovery (instead of waste recycling) in the agricultural industry. This is where the industry can contribute to sustainability to for ecosystem conservation.

CONCLUSION

Exploration of plant-based fibers has continued to develop due to the growing interest in the sustainable use of crude materials due to the low cost, low density, strength, and local availability of these fibers. Among natural fibers, jute is commonly selected by many authors for controlling soil erosion due to its hydroscopic and superior mechanical properties. Researchers have confirmed that establishing ground cover is more critical for soil protection compared to the type of material chosen for erosion mitigation. Reviews from past studies showed that the research on biocomposites in controlling soil erosion is limited compared to the research on natural fibers used for the same purpose. This is perhaps due to the poor availability and high cost of biodegradable polymers compared to natural fibers, which are abundant and inexpensive. Poor adhesive interactions between the matrix and natural fibers due to the hydrophilic characteristic of the fibers is another major drawback that sometimes limits the development of biocomposites for controlling soil erosion.

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