Evaluation of Discarded Textile and Paper Waste for use in Biodegradable Seedling Pots

By

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Abstract

This study evaluates the efficacy of using textile waste (cotton or polycotton) blended with paper waste (newspaper and corrugated cardboard) to form biodegradable seedling pot. A sequential optimization process utilizing alkali treatment, compressive load, drying, and binding agent on the tensile strength of homogeneous sheets (cotton, polycotton, newspaper, and corrugated cardboard) were determined. Thereafter, a bio-composite blends of cotton and polycotton with paper waste was performed to determine an optimum blend of substrates with improved tensile and bending strength properties. A bio-composite blend of cotton (20% cotton, 40% newspaper, and 40% corrugated cardboard) and polycotton (20% polycotton, 40% newspaper, and 40% corrugated cardboard) with an optimum strength were formed into seedling pots. The appreciated seedling pots (untreated blends of cotton and polycotton) were compared with the commercial pots (cardboard seed starter pot and Jiffy pot) in terms of mechanical properties (tensile and compressive strengths), biodegradability (soil burial test and anaerobic digestion), and seed germination. The untreated blends of cotton and polycotton pots demonstrated a comparable optimum strength, while the Jiffy pot and cardboard seed starter pot obtained the least tensile and compressive strengths, respectively. The anaerobic biodegradability assay suggests that the cotton blend pot, polycotton blend pot, and cardboard seed starter pot can degrade anaerobically because of its high biogas and methane generation potential. Furthermore, the soil burial test relates with the anaerobic degradability assay. A 100% seed germination rate was observed from the four seedling pots tested. Thus, the results demonstrated the efficacy of utilizing textile waste to develop seedling pot with desirable strength and biodegradability compared to the tested commercial seedling pots.

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Chapter 1: Introduction

1.1 Global Issues on Textile Industry

Population growth along with the improvement in living standard, the increasing assortment of textile materials, and the decreasing life cycle of textile products has contributed to high global fiber consumption that generates significant amount of post-industrial and post-consumer fiber waste (Wang, 2010; Lin, 2012). Globalization of apparel industry allows production of more clothing at lower cost and many consumers adapt a "fast fashion" trend that consider clothing to be a disposable product (Claudio, 2007). Fast fashion characterized by mass production, variety, agility, and affordability has created a plethora of apparel consumption (Bukhari et al., 2018). Rising cost associated with textile manufacturing in terms of energy, raw materials, and waste management are putting pressure on businesses across the globe. In this regard, it is crucial to understand that the 20th century approaches are not meeting the 21st century demands for sustainable development (Chavan, 2014). It is essential to consider the efficient management of natural resources that offer a sustainable approach for textile waste management by reducing the consumption of resources through reuse and recycling of textile products, which are considered waste. To improve the current behavior of clothing consumption and waste generation, an environmentally and financially sound long-term national program should be established (Ekstrom & Salomonson, 2014).

The clothing and textiles constitute 6% of the global exports of manufactured goods (Figure 1.1). China and the European Union are the two leading regions for clothing and textile exports (WTO, 2018). China is the largest economy in terms of clothing and textiles exports in the world where the production value of textile industry was accounted for 7% of the country's GDP (China Textile Industry Overview 2017-2021). However, the industry is facing challenges such as the instability of the trading environment, changing currency exchange rates, and increasing energy price (Shen, 2008). Moreover, the manufacturing process of textiles is considered environmentally unsustainable (Spuijbroek, 2019). The country's dominance in textile production is challenged by the loss of competitive advantages in terms of low labour and environmental costs.

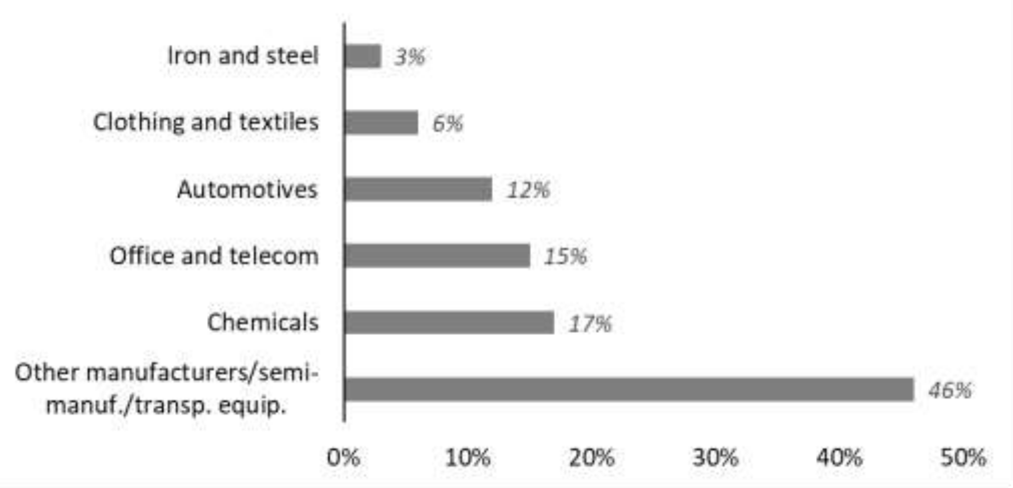


Figure 1.1. Global exports of manufactured goods in 2017 (WTO, 2018)

The worldwide production volume of textile fibers was increasing. For instance, in 1975, about 23.9 million metric tonnes (MMT) of textile fibers were produced and that numeric rose to a staggering 98.5 MMT in 2017 (Statista, 2018). Dominant fibers worldwide such as polyester and cotton are deemed to continuously increase in terms of fibers demand growth (Textile World, 2015; IHS Markit, 2019). Furthermore, the worldwide fiber consumption consists of 40% cellulosic and 60% synthetic fibers, where polycotton is a typical example of the majority of the textiles (GFA & BCG, 2017). Thus, the textile waste management is a global issue that presents huge challenges for textile industry, policy makers, and consumers.

1.2 Textile Waste Generation

Textile waste is generally considered as discarded or unwanted material from the production of fiber, textile, and clothing that can be generated from a number of streams including the fiber, textile and apparel industry, consumers, and the commercial and service industries (Caulfield, 2009). It can be categorized into three types, the pre-consumer, post-consumer, and industrial waste (Chavan, 2014). The pre-consumer textile waste is considered as “clean waste”, which is the by-product of the manufacturing process of fibrous materials. Post-consumer textile waste consists of discarded garments or household textiles (sheets or towels) that are worn-out, damaged, and outgrown that are worthless to consumers after their service life (Domina & Koch, 1997). Industrial textile waste is deemed as “dirty waste” that is generated from commercial and industrial textile applications.

The expansion of clothing and textile industry along with the consumer’s fast fashion trends has caused a rapid increase of textile waste globally. The increased consumption of fashion textile generates a growing amount of waste. As fashion textiles are almost 100% recyclable or reusable, ideally, textile and apparel industry should not generate any waste. Ideally, more than 60% of all recovered clothes could be reused, 35% could be converted into wipers and fiber recycling, and only 5% would need to be discarded (BIR, 2014). However, in real scenario, large fraction of textile waste are disposed into landfills. Hence, it is important to understand the challenges faced by the emerging economies in textile waste management.

The fraction of textiles waste in MSW stream in the U.S. are mainly found in discarded clothing. Furthermore, other sources of textile waste were identified to be furniture, carpets, tires, footwear, and other non-durable goods such as sheets and towels (USEPA, 2018). The amount of textile waste generation and the fraction of textile waste in MSW is increasing with time. An estimated 13.2 MT of textiles waste were generated in 2010, which constituted to be 5.3% of total MSW generation. While in 2017, the generated textile waste increased to 16.89 MT with 6.3% textile waste fraction in MSW stream (Figure 1.2). In Canada, an average person discards 81 pounds of textiles waste each year and 95% of those clothes could be reused or recycled (WRW, 2017; Recycling Council of Ontario, 2018). Another report suggests that an average Canadian discards between 30 pounds (TWD, 2013) and 55 pounds (Marsales, 2016) of textiles annually. Furthermore, the EU textile industry generates approximately 16 MT of waste while discarding 5.8 MT of textiles. From this, only 26% of waste is recycled and the major fraction of this waste is disposed into landfills or incinerated (EC, 2017; Bukhari et al., 2018). The cost of textile waste sent to the landfills is about €60 per tonne in some European countries including France (EC, 2002).

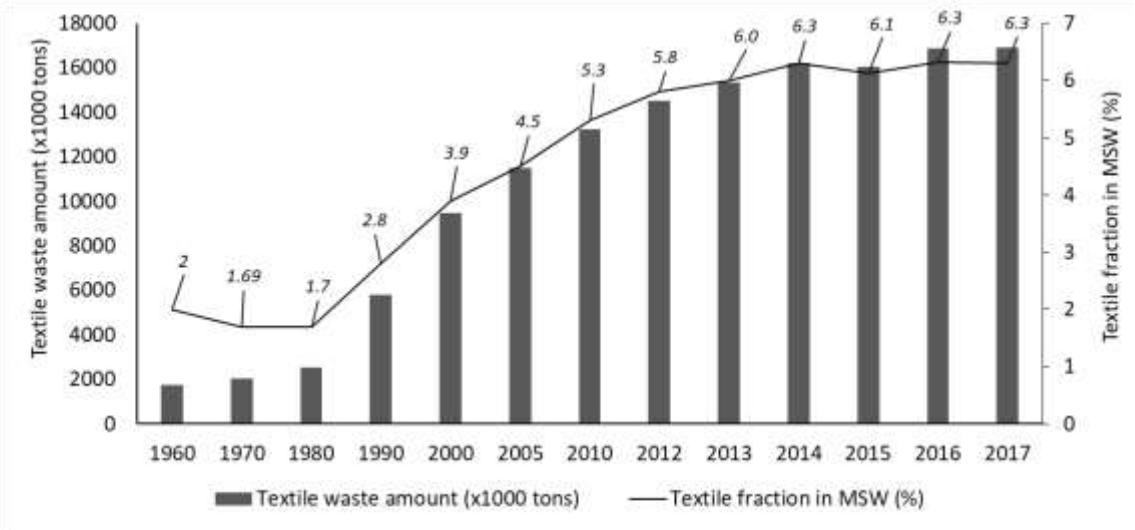


Figure 1.2. Textile waste generation in the US
(USEPA, 2014; USEPA, 2019a; USEPA, 2019b)

1.3 Textile Waste Disposal and Management

Globally, textiles waste generation has increased considerably because of the rise in clothing consumption and production. In the U.S., approximately 85% of all textiles end up in landfills and only 15% are donated or recycled. Among the leading economies in textile industry, the U.S. produces the highest share of landfilling textile waste, which amounted to 29.3 kg/ca in 2016 (Figure 1.3). USEPA (2010) estimated that textile waste occupies nearly 5% of all landfill space.

The estimated cost of textile waste sent to landfill is $45 per ton (Wicker, 2016). Since landfilling keeps the largest share in textile waste management in the U.S., it can be sought that recycling technologies will gain increasing attention to many textile industries. Composting is not a prevalent practice of managing textile waste; however, incineration and recycling are gaining momentum in textile waste management (Figure 1.4).

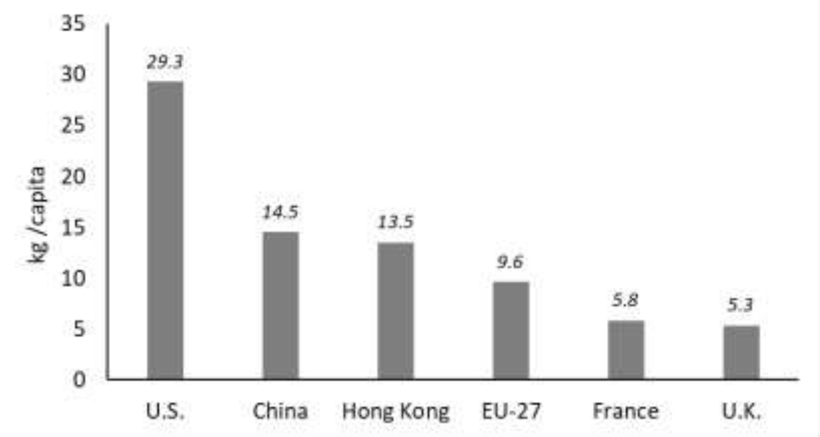


Figure 1.3. Annual amount of landfilled textiles (in kg/ca) in 2016 (Bukhari et al., 2018)

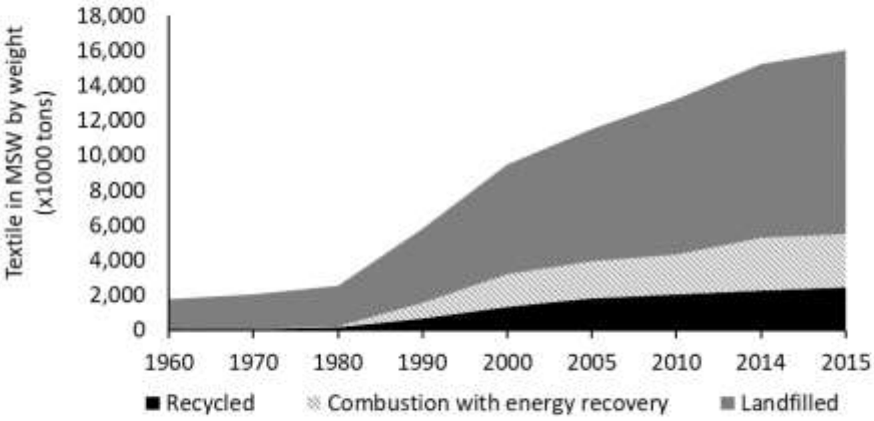


Figure 1.4. Textile waste management pathway (USEPA, 2018)

In Canada, an estimated 500,000 tonnes of apparel waste goes to disposal annually (Storry & McKenzie, 2018). Weber (2015) conducted a survey study in Toronto to determine if the participants donate and/or dispose their unwanted clothes. The study revealed that 17% of the participants consider “disposal” as the most convenient (10%) and fastest way (7%) to get rid of unwanted textile waste. In Ontario, approximately 1.2 million people disposed unwanted clothes into the waste bin at a rate of roughly 45,000 tonnes per year (Weber, 2015). In Vancouver, an estimated 30,000 tonnes of textiles waste are annually landfilled, accounting for 5% of total annual waste volume in 2016 (Tetra Tech, 2015). Unwanted clothing items potentially intended to be donated are usually dropped at the drop off bins within the city or collected by a non-profit charitable organizations) and municipal programmes. Some of the donated textiles are often sent to the landfills due to very poor textile condition (Lyons, 2017). Furthermore, roughly, 45% of the textiles produced in China are wasted and approximately 26 million tons (MT) of garments are left untreated and dumped annually, while only 3.5 MT of the collected textile waste were recycled and reused in 2017 (Collective Responsibility, 2018). Textile waste generation in China is estimated to vary from 20 to 26 MT of waste textiles annually with low utilization rate (Spuijbroek, 2019).

The Chinese government is actively promoting companies to recycle clothing of their own brands through mechanical and chemical recycling and in the absence of effective recycling practices, the prevailing approach is to send used clothes to waste-to-energy (WTE) incinerators (Collective Responsibility, 2018). A circular economy approach was deemed beneficial for the environment and the market for textile recycling. In 2013, China’s State Council required textile industries to develop a circular value chain that promote environmental sustainability in the disposal of post-consumer textiles (Spuijbroek, 2019).

The European Waste Framework Directive (2008/98/EC) defined the fundamental waste management principle to adopt waste management hierarchy (prevention, reuse, recycling, and disposal) in waste management plans and waste prevention programmes (EC, 2008). The European

Council (EC) further promoted sustainability by proposing to substitute the Waste Framework Directive by a Circular Economy Package, which set a target for Municipal Solid Waste (MSW) recovery to 70% and limit the fraction to be landfilled to 10% by 2030 (European Parliament, 2017). The Extended Producer Responsibility (EPR) policy was deemed essential in achieving such targets by setting the producers responsible for the collection, processing/treatment including recycling, and disposal of products at the post-consumer stage of a product's life cycle. In addition, the EPR policy could provide incentives on waste prevention at source, promote green product design, and support public recycling (OECD, 2001). The significant factors contributed to the success of EPR-based environmental policies were the producer's financial responsibility and separate collecting and recycling agencies (Gupt & Sahay, 2015). Since 2006, the implementation of EPR policy in France has contributed to a threefold increase in the collection and recycling rates of post-consumer textile (Bukhari et al., 2018).

Moreover, the EU sets out new rules for waste management, particularly on closed-loop recycling from production and consumption to waste management, to target economies to be more sustainable and environmentally-friendly (EC, 2018). The closed-loop system minimizes waste by repeatedly recycling and reusing materials until they become biodegradable waste. The system can sustainably address the finite land, water, and energy resources used intensely by the fashion industry (GFA & BCG, 2018). The increase in reuse and recycling targets for municipal waste is set for the EU member states: 55% by 2025, 60% by 2030, and 65% by 2035. A separate collection of textiles and hazardous waste from household will be implemented by January 2025 (EC, 2018). Across the European countries, only 18% of clothing is currently being reused and recycled while 30% is incinerated and the major fraction (70%) is being landfilled (GFA & BCG, 2017). In France, 40% of the post-consumer textiles collected are exported to African countries for reuse.

As of 2017, France is the only country in the world that has introduced EPR for textiles, linen, and shoes (Bukhari et al., 2018). Research has also suggested that European companies are more advanced in formulating detailed sustainability targets where the raw materials, design and development, manufacturing, and end-of-use is the priority (GFA & BCG, 2018).

1.4 Textile Reuse, Recycling, and Recovery Technologies

Generally, textile reuse and recycling reduces environmental impact because it can potentially limit the extraction of resources for virgin textile fibers and avoid harmful processes further downstream in the product life cycle. Moreover, textile reuse and recycling is more sustainable when compared to incineration and landfilling. However, reuse is considered more beneficial than recycling, particularly when reusing phase is sufficiently prolonged (Sandin & Peters, 2018). Textile reuse encompasses various means for extending the useful service life of textile products from the first owner to the next (Fortuna & Diyamandoglu, 2017) and this is commonly practiced by renting, trading, swapping, borrowing and inheriting, facilitated by second-hand stores, garage sales, online and flea markets, and charities. On the other hand, textile recycling refers to the reprocessing of pre-consumer and post-consumer textile waste for use in new textile or non-textile products.

Textile recycling is typically performed through mechanical or chemical processes. Mechanical recycling transforms waste into items to be used in decoration, construction, agriculture, and gardening. Chemical recycling involves a process where polymers are depolymerized (polyester) or dissolved (cotton and viscose). Chemical recycling can produce fibers of similar quality compared to the virgin materials (Sandin & Peters, 2018; Collective Responsibility, 2018). The sorted textile waste could be chemically treated to extract resources such as protein-based fibers for producing wood panel adhesives and cellulosic fibers for bioethanol production (EC, 2017).

New chemicals and plastic bottles can be produced by recovering Polyamid (PA) and polyester (PET) from textile waste.

According to Sandin & Peters (2018), textile-recycling route can be classified based on the nature of the processes involved or the level of disassembly of the recovered materials. If the fabric of a product is recovered and reused in new products, it is known as fabric recycling. If the fabric is disassembled, but the original fibers are preserved, it refers to fiber recycling. Correspondingly, if the fibers are dissembled, but the polymers or oligomers are preserved, it is known as polymer/oligomer recycling. Similarly, if the polymers/oligomers are dissembled, but the monomers are preserved, it refers to monomer recycling.

Moreover, textile recycling can be classified into upcycling, downcycling, closed-loop, and open-loop recycling. If the product made from recycled material is of higher quality or value than the original product, it is termed as upcycling; contrary of this is known as downcycling. Closed-loop recycling refers to the utilization of a recycled material in a similar product as its original source, whereas open-loop recycling refers to use of a recycled product in different streams than the original source. Closed-loop recycling has been employed to produce a product of equivalent quality as the virgin material from raw material that produced a polymer product (Wang, 2010).

Furthermore, the recycling technologies for fibers are typically divided into primary, secondary, tertiary, and quaternary approaches. Primary approach involves recycling industrial scraps and the secondary recycling involves mechanical processing of a post-consumer product. Tertiary recycling involves processes such as pyrolysis and hydrolysis that converts plastic waste into chemicals, monomers, or fuels. Quaternary recycling refers to utilization of heat generated from burning the fibrous solid waste (Wang, 2010).

Upcycling and closed-loop recycling are the potential recycling routes that have a minimal environmental impact and also maximize conservation of resources such as raw materials, water and energy (Chavan, 2014). Moreover, textile reuse and recycling have been shown to reduce environmental impact compared to incineration and landfilling, and reusing is more beneficial than recycling (Sandin & Peters, 2018). An ecological footprint concept as an environmental sustainability indicator in a textile tailoring plant revealed that the resources category has the highest ecological footprint due to the high value associated with the cloth, followed by the energy consumption, and the waste category (Herva et al., 2008). The resources recovery can provide major environmental gains since they may be able to replace products from primary resources (Zamani, 2014).

Nowadays, various technologies can be employed to improve textile waste recycling and recovery. Most popular technologies that have been implemented for textile waste management are anaerobic digestion, fermentation, and composting. Other promising techniques of thermal recovery and conversion of textile waste into insulation/building materials are also discussed.

1.4.1 Anaerobic Digestion

Anaerobic digestion is widely used for treatment of biodegradable fraction of organic waste for biogas production. However, very limited studies exist on biogas production using cotton waste (Ismail & Talib, 2016). Cotton is characterized by higher cellulose content (>50%), which is a potential substrate for biological conversion (Raj et al., 2009). Cotton wastes such as cotton stalks, cotton seed hull, and cotton oil cake are potential substrates to produce biogas (Isci & Demirer, 2007). Cotton waste from spinning mills generated higher methane concentration of 77% and 60% with the use of cow dung and goat dung as inoculums, respectively (Ismail & Talib, 2016). The digested slurry of cotton waste from spinning mills can be converted into compost through vermicomposting (Raj et al., 2009). Inoculum addition using cattle manure significantly enhanced biogas production than the substrate alkaline pre-treatment and the thermophilic condition improved the biogas yield by approximately 92% (Ismail & Talib, 2016).

Pre-treatment of the cotton fraction of waste jeans using 0.5 M sodium carbonate (Na_2CO_3) at 150°C for 120 min improved the biodegradability of cotton waste with methane yield of 328.9 mL/g VS (Hasanzadeha, 2018). Pre-treatment of waste jeans textiles using N-methylmorpholine-N-oxide (NMMO) doubled the methane yield up to 400 mL CH_4/g VS/day using two-stage semi-continuous anaerobic digestion process (Jeihanipour et al., 2013). Thus, inoculum addition, pre-treatment, and operating temperature are significant aspects in anaerobic digestion using cotton waste to enhance the biogas and methane yields. Table 1.1 shows the optimum operating conditions for anaerobic digestion using cotton waste.

Table 1.1. Optimum operating conditions using cotton wastes in batch process

Reference	Pre-treatment	Inoculum	Operating temperature	Digestion time	CH_4 yield	% CH_4
Isci & Demirer (2007)	-	Effluent from WWTP anaerobic digester	35±2 ºC	23 days	65 mL/g cotton stalks, 86 mL/g cotton seed hull, 78 mL/g cotton oil cake	60%
Sundar Raj (2009)	-	5 – 7.5% cow dung/pig dung	30-32 ºC	50 days	-	77%
Ismail & Talib (2016)	Alkaline (Na_2CO_3)	Cattle manure	55 ºC	90 days	37.57 mL/g VS	60-70%
Hasanzadeh et al. (2018)	0.5 M Na_2CO_3 at 150ºC for 120 minutes	Effluent from municipal WWTP anaerobic digester	37ºC	40 days	328.9 mL/g VS (60% cotton); 361.08 mL/g VS (pure cotton)	-

1.4.2 Fermentation

Fermentation process involves the conversion of sugar into ethanol with the aid of yeast. Prior to fermentation process, an enzymatic hydrolysis with the aid of enzymes was deemed necessary to transform cellulose to fermentable sugars (Raj et al., 2009). The cotton fraction of waste blue jeans containing 40/60 polyester/cotton blend was investigated for ethanol production. Cellulose enzyme was used to produce hydrolysates with the highest sugar content and was subsequently fermented using *Saccharomyces cerevisiae* for ethanol production. The pre-treatment using 1 M Na_2CO_3 at 150ºC for 120 minutes produced the highest glucose yields via enzymatic hydrolysis of 88.0% and 81.7% for cotton and waste jeans, respectively. The maximum ethanol yields of 69.4% and 59.5% were obtained from cotton and waste jeans, respectively (Hasanzadeha et al., 2018). Cotton gin waste as feedstock for ethanol production was first studied at the Texas Tech University in 1979 (Hamawand et al., 2016). The majority of waste textiles consist of polycotton (polyester-cotton) that contain the blend of biodegradable fiber (cotton) and synthetic fiber (i.e. polyester). Pre-treatment of the cellulose part of a polyester-cotton textile using NaOH/urea at -20ºC increased the ethanol yield to 70% by simultaneous saccharification and fermentation (Gholamzad et al., 2014). Moreover, corona pre-treatment of non-mercerized and mercerized cotton fabrics led to an increase in glucose and ethanol yield. Mercerized cotton fabric was found to be superior with an ethanol productivity of 0.900 g/L·h and ethanol yield of 0.94 g/g glucose after 6 h of fermentation. The obtained results show that the cotton fabric could be an alternative feedstock for the bioethanol production (Nikolić et al., 2017).

1.4.3 Composting

Composting is considered a natural phenomenon of biodegradation of organic waste like cotton waste into a valuable soil supplement. It is considered a low technology process that reduces the volume of organic waste by up to 50% (Hamawand et al., 2016). Composting utilizes various aerobic microorganisms, including bacteria and fungi to convert complex organic matter into simpler substances. Cotton waste poses a significant waste disposal problem nowadays and composting was viewed as an alternative in preventing the direct landfill disposal of cotton waste. Composted and vermicomposted cotton waste could act as a good long-term nutrient source (Mahitha et al., 2016).

Vermicomposting is a biotechnological composting process that enhances the rate of decomposition by the utilizing earthworms (Mahitha et al., 2016). This process is widely known to convert waste into compost with improve soil fertility that greatly exceeds the conventional composting technique. Vermicomposting has been readily implemented for cotton waste. For instance, the bacterial diversity show that the number of bacterial isolates in compost and vermicompost samples of cotton waste was similar; however, the vermicompost samples contain rich density of bacterial isolates when compared with compost samples thereby producing better humus (Selvi & Koilraj, 2015).

The fibers from willow waste of ginning textile factories are considered too short and undesirable for textile applications and are typically disposed into landfills. For this, composting of cotton textile waste utilizing willow waste as a substrate is an alternative solution. Willow waste mixed with cow dung slurry, enzymes isolated from cow dung (cellulase and amylase), and effective microorganism solution showed to have completely decomposed after 20 days. Henceforth, earthworms were introduced for vermicomposting process until the waste mixture turned into light brown or dark brown after 14 days. The resulting vermicompost was used to grow plants in pots and had very good growth rate in terms of root length, shoot length, and leaf area index when compared to the control pot (Aishwariya & Amsamani, 2012). Cotton gin waste is the by-product from a machine that separates cotton fibers from their seeds. It is composed of fragments of burs and stems, immature cottonseed, lint, leaf fragments, and dirt (Myer, 2007). Furthermore, cotton gin waste cannot be directly reused on the farm due to hygiene risks and composting of cotton gin waste is an accepted method (Hamawand et al., 2016). Composting of cotton gin waste with higher proportion of pig slurry at a ratio of 3:4 had greater organic matter humification and higher nutrient concentrations (Santos et al., 2016).

1.4.4 Fiber Regeneration

Sustainability in textile industry depends on the system's ecological footprint that are less damaging to the environment. Since "export for reuse option" is no longer a sustainable alternative for second-hand clothing in many developing countries and the production of virgin cotton fibers necessitates an extensive use of resources, a closed-loop upcycling technology for waste garments that promotes fiber regeneration from textile waste can be a viable solution (Haule et al., 2016). Moreover, pre-treatment of the separated constituents from the waste stream can be further utilized to yield value-added products.

Pre-treatment of waste cotton fabrics using NMMO solvent can completely dissolve cellulose without any degradation and it is environmentally safe to use (Woodings, 1995). A waste cotton fabrics made into pulp and dissolved in NMMO solution and spun into fibers. Pulp reclaimed from cotton-based waste garments can be potentially blended with wood pulp to make fibers with similar properties to lyocell. A lyocell is a generic name for a regenerated cellulose fiber made from dissolving wood pulp using organic solvent (Chavan & Patra, 2004). Pre-treatment of waste textiles using phosphoric acid (H_3PO_4) can potentially recover a non-degradable polyester (PET) fiber and glucose after a subsequent enzymatic saccharification of regenerated cellulose (Shen et al., 2013). Four pre-treatment conditions were investigated including phosphoric acid concentration, pre-treatment temperature, time, and ratio of textiles and phosphoric acid. The maximum sugar recovery of 79.2% at the optimized conditions of 85% phosphoric acid at 50 ºC for 7 h and the ratio of textiles and phosphoric acid of 1:15 yielded 100% polyester recovery.

Textile waste used as substrate for cellulase production by submerged fungal fermentation (SmF) using fungal cellulase and commercial cellulase reveals that the glucose recovery yield of 41.6% and 44.6% were obtained using fungal cellulase and commercial cellulase, respectively. The proposed process has a great potential in treating textile waste for the recovery of glucose and polyester as value-added products (Wang et al., 2018).

1.4.5 Building/Construction Material

Textile materials, particularly the second-hand clothes, represent a source of raw materials that are environmentally friendly and economically profitable. Common application of reusing textile waste in building or construction includes insulation materials for noise and temperature control, and as fillers or reinforcements of concrete. The use of composite materials either from waste or recycled products used in the construction areas, certifies sustainability and the environmental friendliness (Pichardo, 2018). In an investigation on the influence of synthetic fibrous materials for improving the strength characteristics of a fine sandy soil, Ghiassian et al. (2004) explored the conversion of fibrous carpet waste into a value-added product for soil reinforcement. The results clearly illustrated that fibrous inclusions derived from carpet wastes improved the shear strength of silt-rich sands. Moreover, textile reinforced concrete (TRC) innovated by the construction industry was regarded as a means to recycle the high amount of waste from textile industry. It is a combination of fine-grained concrete and multi-axially oriented textiles and several studies have explored the structural functionality, ease of production, applicability, and design aspects (Williams et al., 2015).

1.4.6 Thermal Recovery

Incineration with thermal recovery of unwanted textiles that is not suited for recycling (carpets) is considered a viable alternative to landfilling. Carpet fibers have high calorific value that can reduce the need for fuels and the resulting ash can be used as raw material for cement (Wang, 2010). The biggest advantage of incineration is to recover energy via combustion from unsorted textile waste. However, burning textiles alone can cause irregular temperature behaviour, ignition rate, and the percentage of weight loss in the ignition propagation stage. Therefore, textiles waste should be mixed with waste cardboard upon incineration to maintain a uniform burning behaviour of textiles (Ryu et al., 2007). Incineration of 1 ton of household textile waste can recover 15,800 MJ of energy and generate 27 kg of ash (Youhanan, 2013).

1.5 Challenges for Textile Waste Management

The global population and industrial growth along with the improvement in living standards have caused a global fiber consumption that generates an alarming amount of unwanted textiles. Textile waste is the fastest growing waste streams in municipal solid waste across the globe. Economic and environmental sustainability should be incorporated into the long-term textile waste management programme. Although, the application of EPR policy in textile waste is still limited, it is considered to be essential in promoting a circular economy system. EPR makes the producers responsible for the overall textile waste management from the collection and up to the disposal at the end of product's life cycle. Besides EPR, a holistic approach should be undertaken where major stakeholders (industry, government, NGOs, private agencies, and consumers) must work in unity to promote a dynamic circular system. The emerging economies in textile manufacturing should take the lead in shifting from linear economy to circular economy. Shifting from a current linear economy into a circular economy yields tremendous environmental benefits for the fashion industry while mitigating the effects of greater demand for garments due to an ever-rising world population (GFA & BCG, 2018).

Textile reuse and recycling is more sustainable than incineration and landfilling, but reuse is considered more beneficial than recycling. Textile reuse is the most preferred option, but it suffers a shrinking market due to the ban on import of second-hand clothing in some countries. Textile reuse and recycling to produce new products should be driven by economic incentives to make it feasible to the operating industry. To further reduce the environmental impact, sustainable blended materials are made by utilizing recycled fibers. Designing a textile product by prolonging the service life quality could intensify reuse. In addition, it is essential to promote consumer awareness to foster an environmentally-friendly consumption. Emerging economics should manage their own textile waste in a closed-loop circular approach, especially, since the exporting of textile waste to developing countries is being outlawed. There are various streams of textile recycling technologies available in the market and several others continue to innovate new ideas with biotechnological advancements. The application of holistic technologies and introduction of technologies to manage the complex nature of textile waste are deemed essential.

1.6 Sustainable Option for Textile Recycling

Textile such as cotton, polyester, and polycotton (60% cotton/40% polyester) are the predominant fibers that comprised most of the consumers merchandised (Textile World, 2015; IHS Markit, 2019; GFA & BCG, 2017). Large fraction of textile waste found in MSW stream were disposed in landfills (USEPA, 2018; Bukhari, et al., 2018). Furthermore, the use of plastic or petroleum-based container in greenhouse or nursery production is considered unsustainable due to problems associated with plastic recycling and disposal. Nowadays, the use of biodegradable container in greenhouse or nursery production become popular. This study explores an alternative option of utilizing textile from MSW stream by recycling into a usable form like biodegradable seedling pot. Developing a biodegradable seedling pot from textile waste was not reported in literatures, hence this study attempt to evaluate. Utilization of textile waste for use into usable form promotes textile waste landfill diversion. Furthermore, the use of biodegradable seedling pot or bio-container made from waste resources promotes environmental sustainability and foster consumers' "green" product perception.

1.7 Objectives of the Study

The main goal of this study is to investigate the efficacy of utilizing textile waste blended with paper waste to develop a biodegradable seedling pot. This research consists of two specific objectives. The first objective is to determine the effect of alkali treatment, compressive force, drying operation, and binding agent to the tensile strength of homogeneous sheets. The optimized conditions obtained from the first objective was utilized to perform the second objective which is to develop a biodegradable seedling pot from discarded textile and paper waste.

Chapter 2: Effect of Alkali Treatment, Compressive Load, Drying, and Binding Agent on the Tensile Strength of Discarded Textile and Paper Waste Pulp formed into Sheets

2.1 Abstract

This study investigates the effect of alkali treatment using sodium hydroxide (NaOH) and sodium bicarbonate ($NaHCO_3$) on the tensile strength of homogeneous sheets formed from cotton, polycotton, newspaper, and corrugated cardboard. The substrates were cut into smaller pieces (1 cm x 0.5 cm) and soaked at different concentrations of NaOH (5%, 10%, and 20%) and $NaHCO_3$ (5% and 10%) for 5 h. The treated substrates were turned into pulp and formed into sheets (5 cm x 2.5 cm x 0.1 cm) at 500 N compression load and dried at 60°C for 48 h. To determine the effect of compressive force, a simultaneous study using 200 N load for NaOH treated sheets was performed and compared with 500 N. The effect of different drying temperature and duration (105°C-5h, 60°C-72h, 60°C-48h, 60°C-24h, 40°C-48h, and 40°C-24h) on the tensile strength of untreated (control) homogeneous sheets compressed at 500 N were determined. The influence of binding agents such as blackstrap molasses, sodium alginate, and cornstarch on the tensile strength of the formed sheets were studied. Alkali treatment using 5% NaOH at 5 h soaking demonstrated the highest increase in tensile strength of 21% and 19% for cotton and newspaper, respectively. Increasing compressive load from 200 N to 500 N shows the highest increase in tensile strength of 37% and 42% for cotton and newspaper, respectively. The favourable optimum temperature of 105°C for a drying duration of 5 h demonstrated an improved tensile strength. Remarkably, cornstarch at 20% concentration obtained an increased optimum tensile strength by 395%, 320%, 310%, and 185% for cotton, polycotton, corrugated cardboard, and newspaper sheets, respectively. The optimum results obtained from this study will be utilized to develop a biodegradable seedling pots using discarded textile and paper waste as substrates.

2.2 Introduction

Consumerism and economic growth cause an increasing amount of discarded textile and paper waste in municipal solid waste (MSW), which is mostly disposed in landfills. In 2015, the U.S. generated 16.03 MT (million tons) of textile waste, which is equivalent to 6.11% of the total MSW where 65.7% (10.5 MT) were landfilled (USEPA, 2018). The primary textile waste in MSW comprise discarded clothing including non-durable goods such as sheets and towels. Moreover, paper and paperboard waste represent the largest fraction of the total MSW generated (68.05 MT) and recycled (45.32 MT) in the US, but it was the 3rd largest fraction of MSW (18.30 MT) disposed in landfills (USEPA, 2018). Cellulose fibers from waste paper that are recycled 5-6 times become short and weak due to repeated treatment and drying operations (Munuy, 1996; Chen et al., 2012). These deteriorated cellulose fibers cannot be recycled and eventually end up in landfills. Discarded textile and paper waste are considered fiber-rich resources that can be potentially downcycled into valuable products and thereby promote landfill disposal diversion.

This study aims to investigate the efficacy of using discarded textile and paper waste as substrates to form sheets with optimum tensile strength by evaluating the effect of alkali treatment, compressive force, drying, and binding agents. The homogeneous substrates such as cotton, polycotton, newspaper, and corrugated cardboard were treated using NaOH and $NaHCO_3$ under different concentrations and soaking time. Moreover, the effect of increasing compressive load from 200 N to 500 N on the tensile strength of the sheets was determined. Furthermore, different drying conditions of 103°C-5h, 60°C-72h, 60°C-48h, 60°C-24h, 40°C-48h, and 40°C-24h were investigated. Finally, the effect of different binding agents such as blackstrap molasses, sodium alginate, and cornstarch at different concentrations of 5%, 10%, 15%, and 20% was also studied.

2.2.1 Alkali treatment

Utilization of fibrous waste materials from MSW stream such as discarded textile and paper waste promotes landfill waste diversion and offers ecological benefits. Natural fibrous waste materials are lignocellulosic, i.e. primary composition includes cellulose, hemicellulose, and lignin (Table 2.1). Cellulose has a linear framework of semicrystalline structure that provides fiber strength, stiffness, and stability, hemicellulose consists of branched polymer structure that is fully amorphous, and lignin has an aromatic structure that is also amorphous (Kabir et al., 2012; Frederick & Norman, 2004; Rowell et al., 1997).

Table 2.1. Composition of some fibrous materials

Fibrous materials	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference(s)
Cotton	82.7	5.7	0.7-1.6	Fakirov & Bhattacharyya (2007); Mohanty et al. (2000)
Newspaper	68.5	13.1	23.4	Yuan et al. (2012)
Corrugated cardboard	52.8	13.3	22.2	Gonzalez-Estrella et al. (2017)

Alkaline treatment or mercerization of natural fibers is widely used to improve the cellulosic molecular structure that enhances fiber surface adhesion with the binder (Kabir et al., 2012; Joseph et al., 2003). Alkaline treatment improves the surface roughness of the fiber by partial removal of hemicellulose, lignin, and other organic substances and distorts crystalline cellulose structure thereby increasing the reaction sites (Li et al., 2007; Ray et al., 2001). Several studies have revealed that mercerization using sodium hydroxide (NaOH) and sodium bicarbonate ($NaHCO_3$) improved the mechanical properties of the natural-fiber reinforced composites (Fiore et al., 2018; Fiore et al., 2016; Cai et al., 2016; Yan et al., 2012; Goud & Rao, 2011). Moreover, coir-fiber treatment using 5% NaOH aqueous solution for 72 h resulted in a 31% increase in tensile strength of coir-polyester composite (Jayabal et al., 2012). Also, treatment of paper sheets formed from recycled paper fibres with NaOH/urea solution also improved the physical properties of the sheets (Miao et al., 2018). Therefore, alkaline treatment at the optimum conditions can improve the physical properties of the corresponding composites.

2.2.2 Compressive load

Compression process induces transverse stress that enhances rearrangement of particles to reduce voids. This process compacts a material by releasing trapped air and reduce the gaps between particles. Some studies have reported an improvement in properties of materials upon increasing compressive load. Tensile strength can be improved by the application of compressive force in forming pharmaceutical tablets (Kolakovic et al., 2011; Amin et al., 2012; Juban et al., 2017). Increasing the compaction pressure has also improved the mechanical properties of maize residue pellets (Wongsiriamnuay & Tippayawong, 2015) and biomass grass pellets (Mani et al., 2006). To date, no literature is available that investigated the effect of compression on the tensile strength of discarded textile and paper waste pulp formed into sheets. The effect of compression loads (200 N and 500 N) on the tensile strength of untreated or control homogeneous sheets of cotton, polycotton, newspaper, and corrugated cardboard was investigated herein.

2.2.3 Drying temperature and time

Optimum drying temperature and duration for the homogeneous sheets formed from cotton, polycotton, newspaper, and corrugated cardboard was also addressed in this study. Previous literatures on the development of biodegradable seedling pots from organic waste materials (newspaper pulp, hemp fibres, etc.) employed different drying conditions (Table 2.2). It can be observed that drying temperature and duration requirements are dependent on the biomaterial and its post-drying quality (Dev & Raghavan, 2012). However, optimum drying conditions to attain optimal tensile strength of biodegradable seedling pots or sheets from discarded textiles and paper waste do not exist. Hence, this study will investigate the drying requirements pertaining to optimal tensile strength.

Table 2.2. Drying conditions used for the preparation of seedling pots

Residual substrates	Temperature (°C)	Time (h)	Reference
Biomaterials and banana peels	70	24	Mohd Rafee et al. (2019)
Newspaper pulp fibres and bioplastic	70	24	Liew & Khor (2015)
Recycled wastes of tomato & hemp fibers	40	24	Schettini et al. (2013)
Digested biosolids	60	48	Stone (2017)
Ganoderma lucidum mushroom	60-70	72	Postemsky (2016)
Konjac by-product of industrial waste	110	-	Lina et al. (2013)
Sweet potato distillation residual	60	10	Yamauchi et al. (2006)

2.2.4 Binding agents

Binder either a solid or liquid form and typically dissolve in warm or hot water. It can form a strong inter-particle bonding by forming bridges, coatings or films that can improve the strength of a material. Binders can be classified according to its nutritional source, i.e. protein origin, carbohydrate source, and without nutritional value (De Silva & Anderson, 1995). Among them, the carbohydrate source binder exhibited high molecular diversity to allow a wide range of significant applications in the field of pharmaceuticals, food industry, feed manufacturing, textile industry, composite materials, and packaging. These natural biopolymers are potential binders due to its organic properties. Traditionally, binders have been used to improve the mechanical properties of the resulting composite material.

2.2.4.1 Molasses

Molasses is a thick dark to light brown syrup with distinct smell and sweet taste, which is generated as a by-product of sugar cane production. It is widely used as a binder for composite fuel in the form of briquettes or pellets with improved mechanical properties and fuel characteristics (Jittabut, 2015; Zhai et al., 2018; Adeleke et al., 2019). The recrystallization mechanism of dissolved sugar in molasses at dry state resulted in an enhanced strength of the pellets (Mišljenovic´ et al., 2016). Mostly, molasses as a binder is used in a concentration from 0 to 20%. Recently, molasses is used as an additive in papermaking to enhance the strength of the paper (Fahmy, 2007; Fahmy & Mobarak, 2009). Furthermore, Ashori et al. (2013) demonstrated the improvement on physico-mechanical properties of recycled paper made from an old corrugated container using molasses as a dry-strength agent.

2.2.4.2 Sodium alginate

Alginates are naturally occurring anionic complex polysaccharides derived from the main cell wall of brown seaweeds of *Phaeophyceae* class (Pawar & Edgar, 2012; Holdt & Kraan, 2011; Kloareg & Quatrano, 1988). Alginates are commonly used in many industries because of its unique rheological properties such as thickening, gelling, stabilizing, viscosifying, mucoadhesiveness, and ability of sol/gel transition (Szekalska et al., 2016; Draget et al., 2006). Among various alginates, sodium alginate is the most common salt of alginate and one of the established biopolymers because of its multifunctional properties and a wide range of applications (Yoo & Krochta, 2011; Lee & Mooney, 2012). Sodium alginate consists of complex mixture of oligo-polymers, polymannuronic acid, polyguluronic acid, and a mixed polymer (Smidsrod et al., 1966). Moreover, sodium alginate can be used as a binder for biodegradable seedling pots because they are biodegradable, biocompatible, widely available, renewable, and non-toxic (Avella et al., 2007; Immirzi at al., 2009).

2.2.4.3 Cornstarch

Starch is a popular biopolymer extensively used as a binder that has a vast array of applications due to its properties, abundance, renewability, and low-cost (Wang et al., 2012; Tabasum et al., 2019). Cornstarch or cornflour is the starch of the corn or maize grain taken from the endosperm portion of the kernel. It is white in color and has a powdery feel. Cornstarch is a solution binder that can be dissolved in water upon gradual heating to eventually form a paste or gel with increased viscosity. Cornstarch is one of the traditional additives and it is widely used as fillers or binders in various applications, particularly in food and drug manufacturing. In tablet formulations, cornstarch is a common excipient; a cornstarch paste concentration of 5–25% (w/w) was utilized in tablet granulations (Rowe et al., 2012). A direct relationship between starch content and tensile strength of starch/styrene-butadiene latex composites has been established (Chen et al., 2014). An environmentally sustainable shift from petroleum-based containers to biodegradable containers made of biomass with the incorporation of organic binder like cornstarch is now prevalent. In addition, modified cornstarch was used as an additive with sisal fibre to produce a biodegradable composite to augment the replacement of plastic packing materials (Xie et al., 2018). Cornstarch has also been used as a binder in making biodegradable nursery container (Sun et al., 2017).

2.3 Materials and Methods

2.3.1 Alkali treatment and conversion of waste materials into pulp

The substrate tested for this study includes textile waste in the form of soiled towel (100% cotton) and polycotton fabric (60% cotton, 40% polyester), and paper waste in the form of old newspaper and corrugated cardboard. Solid analysis including moisture content, total solid (TS), and volatile solid (VS) contents were determined for all substrates and binders according to the standard methods (Rice & Bridgewater, 2012). First, these substrates were manually cut into small pieces (1 cm x 0.5 cm) using a kitchen scissor. Secondly, the substrates were weighed and treated using alkali solutions of sodium hydroxide (NaOH) and sodium bicarbonate ($NaHCO_3$) as presented in Figure 2.1.

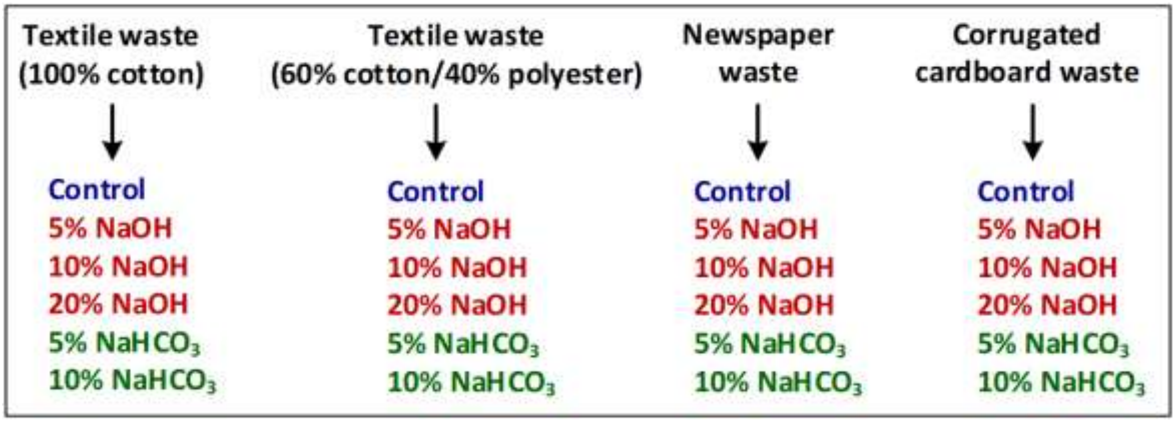


Figure 2.1. Alkali (NaOH and $NaHCO_3$) treatment on substrates

Three different concentrations of NaOH solution (5%, 10%, and 20%) and two different concentrations of $NaHCO_3$ solution (5% and 10%) at 5 h soaking were used. It is worth mentioning that NaOH treatment was performed initially and the tensile strength results were not appreciable for 20% NaOH for all the substrates tested. Therefore, only two different concentrations of $NaHCO_3$ solution (5% and 10%) were considered. Alkali treatment was performed at the room temperature (22°C). Thirdly, after the alkali treatment, the substrates were rinsed using tap water followed by deionized water until a neutral pH was achieved. Then, the treated substrates were converted into pulp using a 2 L blender with 1400 W power (thinkKitchen Pro-vita, made in China) by adding deionized water (hydro-pulping process). The blender was left running 2 minutes, then the substrate was turned into pulp. Finally, the prepared pulps were drained and squeezed to remove excess water using double folded cheesecloth to avoid pulp wastage and weighed accordingly to make sheets considering the resulting dried sheet to be 0.5 g TS. An untreated substrate was also prepared to serve as a control by soaking the substrate in deionized water for 5 h.

2.3.2 Preparation of homogeneous sheets

The weighed wet pulp from each treatment and substrate type were formed into 5 cm x 2.5 cm x 0.1 cm sheets using a fabricated mold as shown in Figure 2.2. The pulps were spread out evenly onto the entire surface of the bottom mold and covered with the top mold to form compacted sheet. The sheet for each treatment and substrate type were compressed by placing the mold on the platform of a universal testing machine (Model 3366 Universal Testing Systems, Instron Corp., Norwood, MA, USA). Henceforth, a load of 200 N or 500 N was applied to the mold by using a 10 kN load cell at a rate of 10 mm/min (Figure 2.3). Upon reaching the desired load, the sheet was held inside the mold for a minute to maintain constant pressure and prevent relaxation. Next, the compressed sheet was removed from the mold and placed on an aluminum tray for drying at 60°C for 48 hours prior to tensile strength testing.

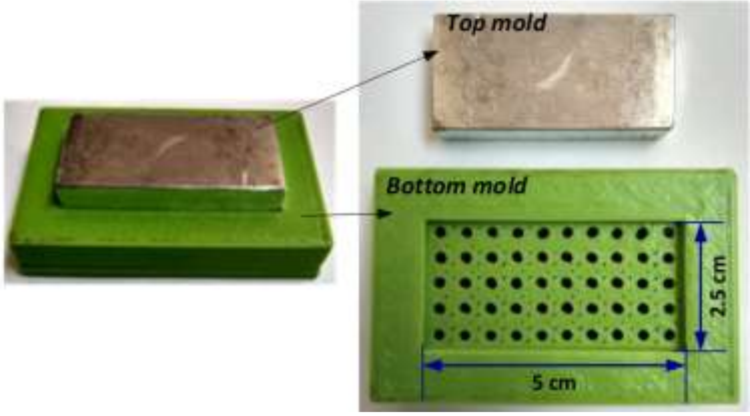


Figure 2.2. Mold used for making sheets

Figure 2.3. Compression set-up to form sheets

2.3.3 Drying temperature and time

Different drying temperatures and durations were studied to determine their effect on the tensile strength of homogeneous sheets produced from textile and paper waste. The substrates used were cotton, newspaper, and corrugated cardboard. Polycotton was not included here and cotton was chosen to represent a textile waste in this part of the study to minimize the number of samples to be tested. The substrates were soaked in deionized water for 5 h and converted into pulp using the method described above. The substrates were compacted into sheets by using a compressive load of 500 N as described in section 3.3.2. Six replicate sheets were tested for tensile strength from each drying condition and substrate type. Six different drying temperature and duration, i.e. 105°C-5h, 60°C-72h, 60°C-48h, 60°C-24h, 40°C-48h, and 40°C-24h were considered to investigate their effect on the tensile strength using untreated homogeneous sheets (control) compressed at 500 N. Figure 2.4 shows the prepared compacted sheets.

2.3.4 Binding agents

The effect of using different binders such as blackstrap molasses, sodium alginate, and cornstarch at different concentrations of 5%, 10%, 15%, and 20% on a dry weight basis were blended with the substrate to form six replicates of homogeneous sheets. The solid analyses of each binder and substrate were determined according to the standard methods described by Rice & Bridgewater

(2012). The effect of the binder on the tensile strength of homogeneous sheets was performed employing the optimum results from alkali treatment of 5% NaOH at 5 h soaking time, compaction force of 500 N, and drying temperature of 105°C for 5 h.

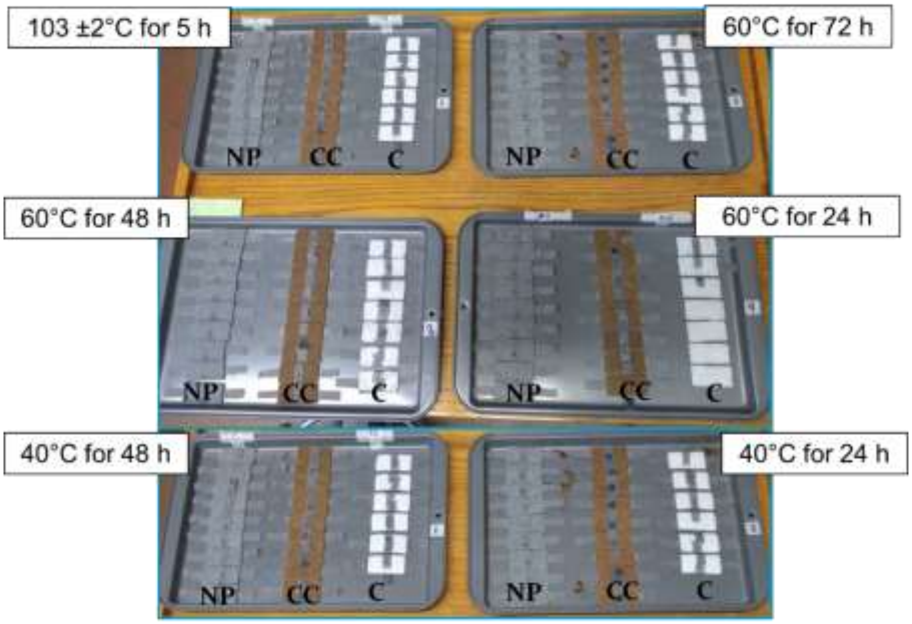


Figure 2.4. Sheets prepared at different temperatures and durations (NP-newspaper, CC-corrugated cardboard, C-cotton)

2.3.5 Tensile strength test

Tensile strength is an important parameter that indicates the handling capacity of biodegradable seedling containers (Castronuovo et al., 2015). In addition, tensile forces are typically exerted on the walls of the container during plant growth and manual transportation (Stone, 2017). A universal testing machine (LS5 Model, Lloyd Materials Testing, Lloyd Instrument Ltd., West Sussex, UK) equipped with 5-kN load cell was used to determine the tensile strength of the prepared sheets (Figure 5). The top and bottom eccentric roller grips of 50 mm length were attached to the machine that hold the sheet while pulling at a set extension rate (testing speed) of 2 mm/min. The bottom grip was kept fixed while the top grip moves upward during tension. The test was set to stop when the sample breaks to enable the test break detection.

Figure 2.5. Tensile strength testing

2.4 Results and Discussion

2.4.1 Effect of alkali treatment

The effect of alkali treatment on the tensile strength of homogenous sheets was studied using NaOH and $NaHCO_3$ at different concentrations for 5 h soaking as presented in Figure 2.1. Besides tensile strength (MPa), a specific tensile strength (MPa/g TS) was also considered to quantify the strength of sheets on a dry weight basis. Figures 2.6-2.9 present the tensile strength results of the formed sheets of cotton, polycotton, newspaper, and corrugated cardboard, respectively. The control represents the untreated sheets. Among the tested treatments, the optimum tensile strength was obtained from 5% NaOH for cotton, polycotton, and newspaper sheets. The highest tensile strength of 4.33 MPa equivalent to 10.82 MPa/g TS was obtained from newspaper sheets (Figure 2.8) followed by cotton sheets having a strength of 3.28 MPa (5.99 MPa/g TS) (Figure 2.6). The lowest strength of 0.52 MPa (0.96 MPa/g TS) was obtained from polycotton (Figure 2.7). For corrugated cardboard, none of the alkali treatments improved the tensile strength because the untreated or control sheets obtained the highest strength as depicted in Figure 2.9. This can be attributed to a lower cellulose content of the corrugated cardboard (Table 2.1) and the cellulose fibers become too short and weak after repeated recycling (Munuy, 1996; Chen et al., 2012). Thus, the results suggest that it is appreciable to soak the corrugated cardboard in deionized water (control), rather than in alkali solution.

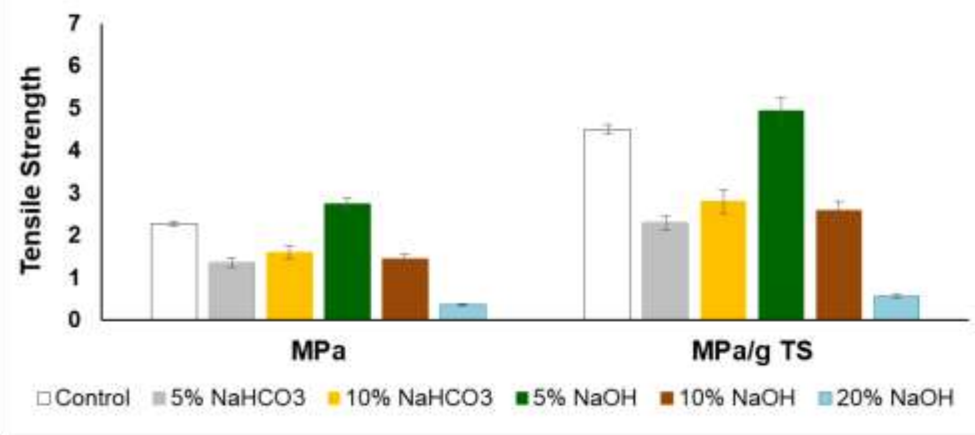


Figure 2.6. Tensile strength of cotton sheets (Error bars indicate standard error of the mean)

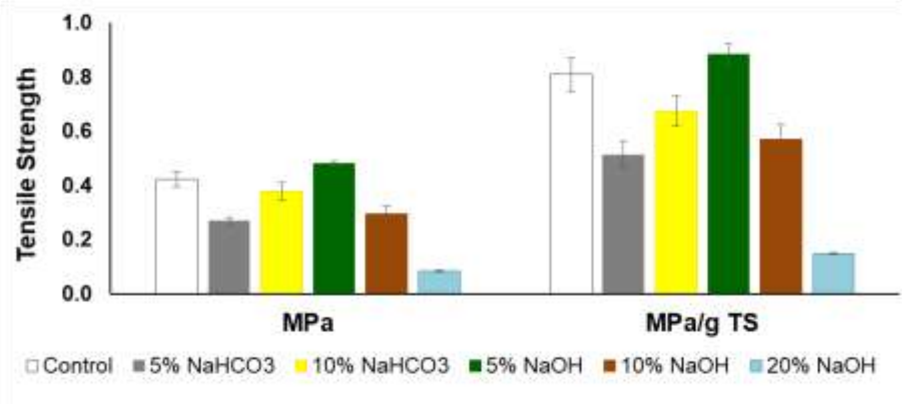


Figure 2.7. Tensile strength of polycotton sheets (Error bars indicate standard error of the mean)

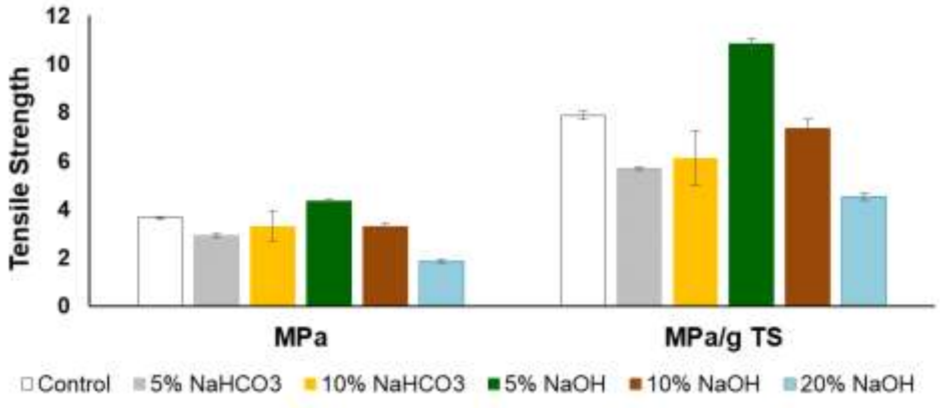


Figure 2.8. Tensile strength of newspaper sheets (Error bars indicate standard error of the mean)

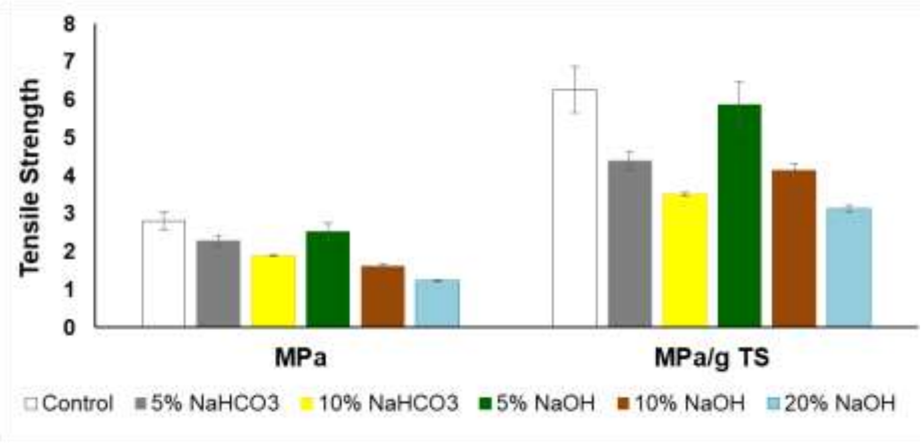
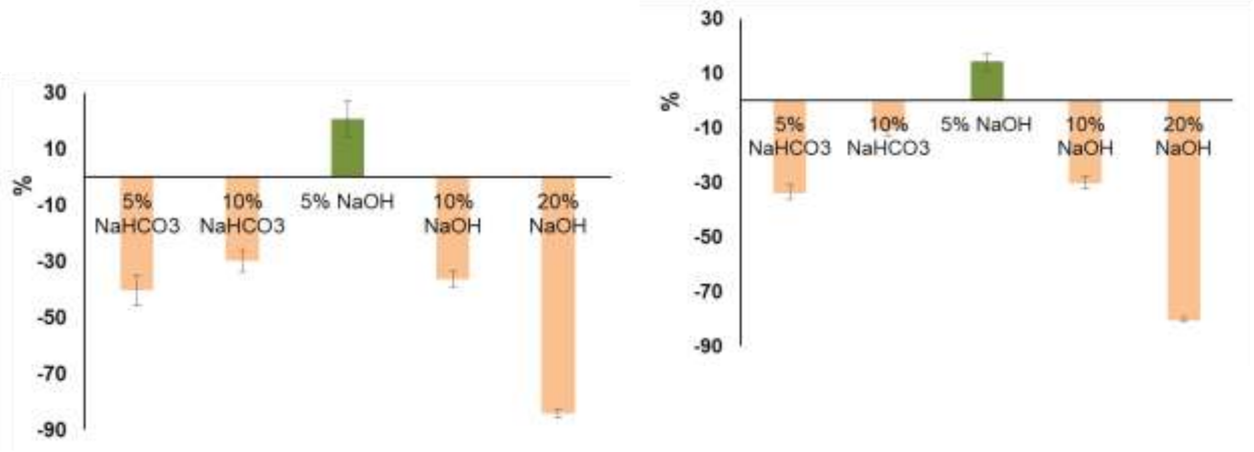
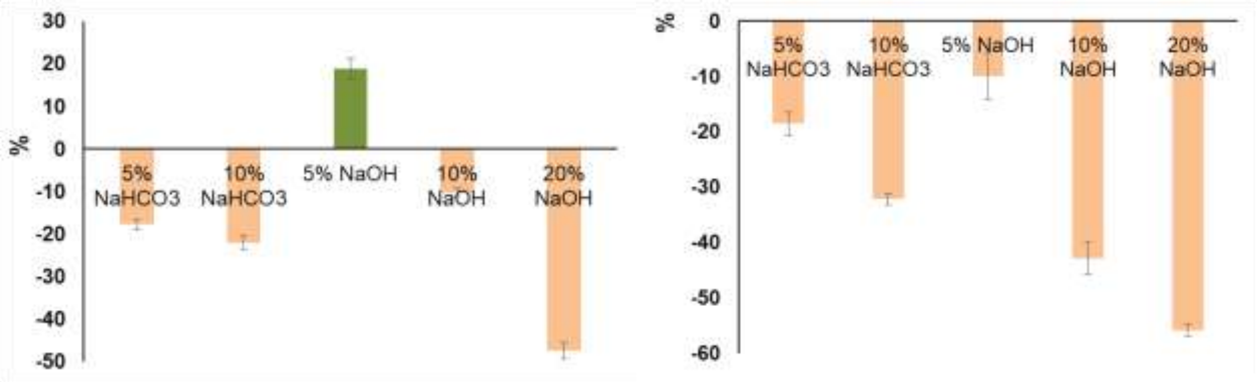


Figure 2.9. Tensile strength of corrugated cardboard sheets
(Error bars indicate standard error of the mean)

To quantify the effect of alkali treated sheets vis-à-vis the untreated ones (control sheets), the optimum results obtained from 5% NaOH were compared to other treatment conditions. It is evident that 5% NaOH at 5 h soaking time increased the tensile strength for formed sheets of cotton, newspaper, and polycotton by 21%, 19%, and 14%, respectively, compared to the untreated ones (Figure 2.10). While for corrugated cardboard sheets, both alkali treatments were not favorable as there was no improvement in tensile strength. From the results, it can be deduced that 5% NaOH treatment for 5 h soaking time was beneficial for the improvement of tensile strength of cotton, polycotton, and newspaper substrates. Hence, alkali treatment is an appropriate step for increasing the tensile properties of cotton, polycotton, and newspaper substrates, but it shows no beneficial effect on the tensile strength of corrugated cardboard.



a. Cotton b. Polycotton



c. Newspaper d. Corrugated cardboard

Figure 2.10. Percentage increase or decrease in tensile strength of alkali treated substrates (Error bars indicate standard error of the mean)

2.4.2 Effect of compressive loads

Figure 2.11 presents the results of tensile strength for all the four substrates treated at different concentrations of NaOH (5%, 10% and 20%) including the untreated (control) substrates under the compressive loads of 200 N and 500 N. The results suggest that for all the substrates under different treatments, the tensile strength improves at a compaction force of 500 N compared to 200 N. Furthermore, cotton, polycotton, and newspaper sheets treated with 5% NaOH compacted at 500 N obtained the optimum tensile strength when compared to 200 N of compaction force.

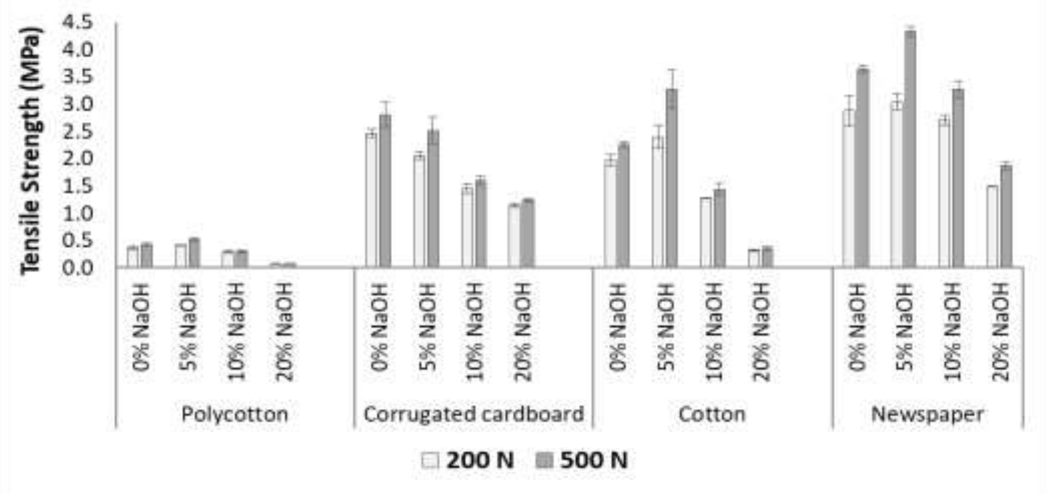


Figure 2.11. Effect of compressive loads (200 N and 500 N) on the tensile strength of the substrates (Error bars indicate standard error of the mean)

Figure 2.12 shows the percent increase in tensile strength from 200 N to 500 N compressive force. The treatment at 5% NaOH caused the highest increase in tensile strength of 42% in newspaper substrate, followed by cotton and polycotton of 37% and 25%, respectively. While, for corrugated cardboard, the 500 N compressive load was also favorable over 200 N, which obtained an optimum tensile strength increase of 12% for untreated sheets.

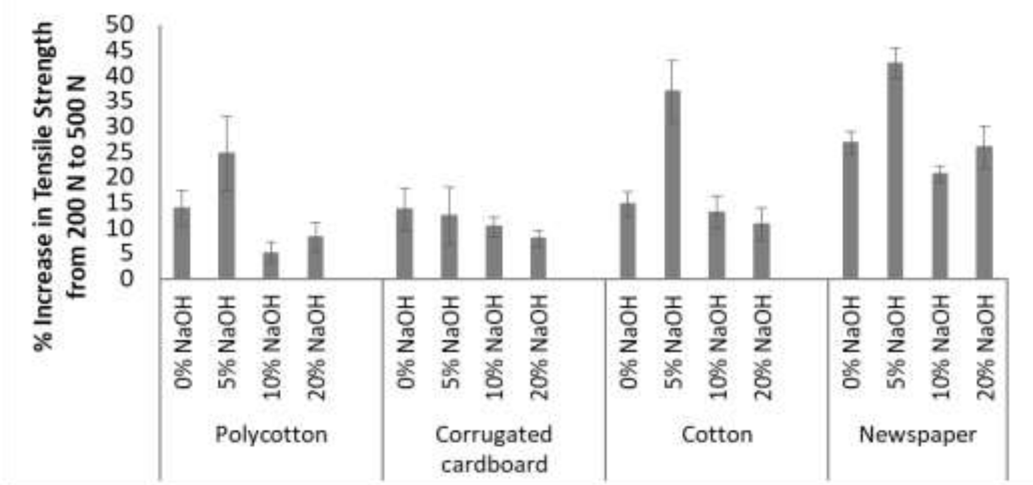


Figure 2.12. Percent increase in tensile strength of compacted sheets at 200 N and 500 N (Error bars indicate standard error of the mean)

2.4.3 Effect of drying temperature and time

Figures 2.13 - 2.14 present the tensile strength and specific tensile strength results of cotton, corrugated cardboard, and newspaper sheets after drying at different temperatures and times. Among the drying conditions tested, an optimum tensile strength can be obtained from 105°C for 5 h, 60°C for 72 h, and 60°C for 48 h treatments. However, an optimum tensile strength of 2.25 MPa (4.28 MPa/g TS), 3.77 MPa (7.60 MPa/g TS) and 4.08 MPa (8.09 MPa/g TS) for cotton, corrugated cardboard, and newspaper sheets were obtained, respectively, after drying at 105°C for 5 h. In terms of tensile strength, the results from this study favor a higher drying temperature of 105°C because the drying process can be performed at shorter time of 5 h.

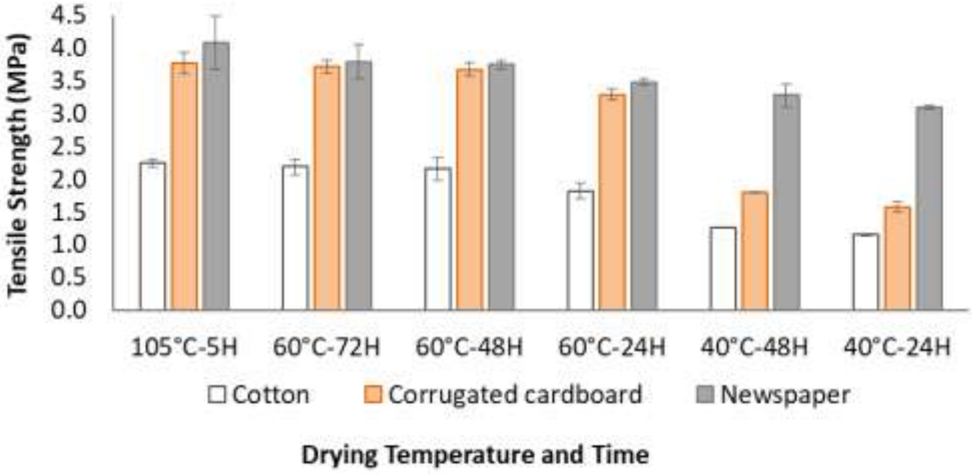


Figure 2.13. Tensile strength of untreated substrates at different drying conditions (Error bars indicate standard error of the mean)

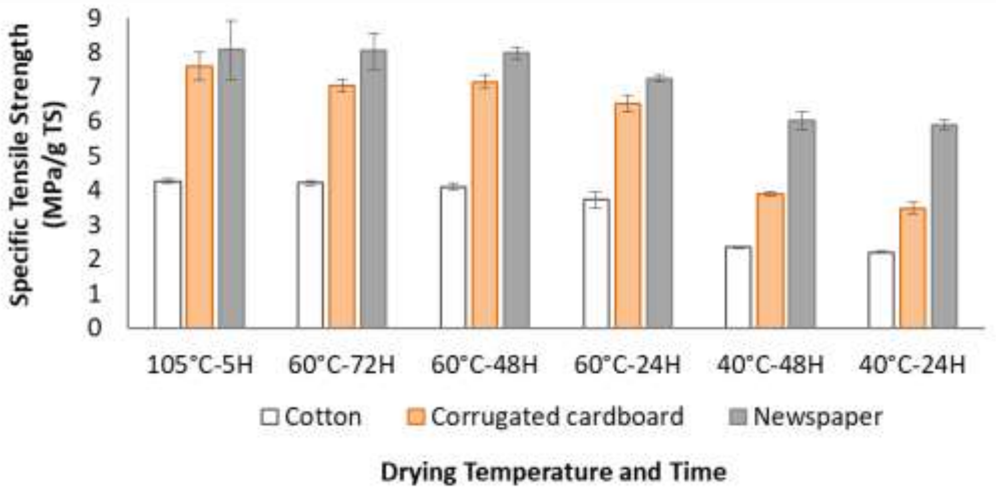


Figure 2.14. Specific tensile strength of untreated substrates at different drying conditions (Error bars indicate standard error of the mean)

2.4.4 Effect of binding agents

The solid analysis results of each binder and substrate were used to determine the amount of each binder at concentrations of 5%, 10%, 15%, and 20% on a dry matter basis is presented in Table 2.3. Figure 2.15 presents the tensile strength results of the substrates using different binders. The results show that cornstarch was the predominant binder in improving the tensile strength of the substrates. Importantly, the added cornstarch at a concentration of 20% on a dry weight basis per sheet achieved an optimum tensile strength of 2.19 MPa, 2.93 MPa, 5.47 MPa, and 6.20 MPa for polycotton, cotton, corrugated cardboard, and newspaper sheets, respectively. The corresponding specific tensile strength values were 3.83 MPa/g TS, 5.10 MPa/g TS, 9.82 MPa/g TS, and 12.31 MPa/g TS for polycotton, cotton, corrugated cardboard, and newspaper sheets, respectively (Figure 2.16). This may imply that the higher tensile strength of newspaper and corrugated cardboard was attractive in blending with textiles waste of lower tensile strength. Moreover, sodium alginate was also effective in improving the tensile strength of the substrates. The results at 20% sodium alginate concentration show that an improved tensile strength of 1.74 MPa (2.97 MPa/g TS), 2.51 MPa (4.32 MPa/g TS), 3.64 MPa (7.43 MPa/g TS), and 4.44 MPa

(9.94 MPa/g TS) for polycotton, cotton, corrugated cardboard, and newspaper, respectively. However, blackstrap molasses as a binder was not effective in improving the tensile strength of the substrates.

Table 2.3. Solid analysis on waste samples and binders

Solid analysis (%)	Substrates				Binders		
	Textile waste		Paper waste		Blackstrap molasses	Sodium alginate	Corn-starch
	Cotton	Poly-cotton	Newspaper	Corrugated cardboard			
Moisture content	3.93	0.60	3.90	2.60	26.64	10.98	10.03
Total solid	96.07	99.40	96.10	97.40	73.36	89.02	89.97
Volatile solid	99.51	99.52	89.61	91.14	91.89	59.94	99.83
Fixed solid	0.49	0.48	10.39	8.86	8.11	40.06	0.17

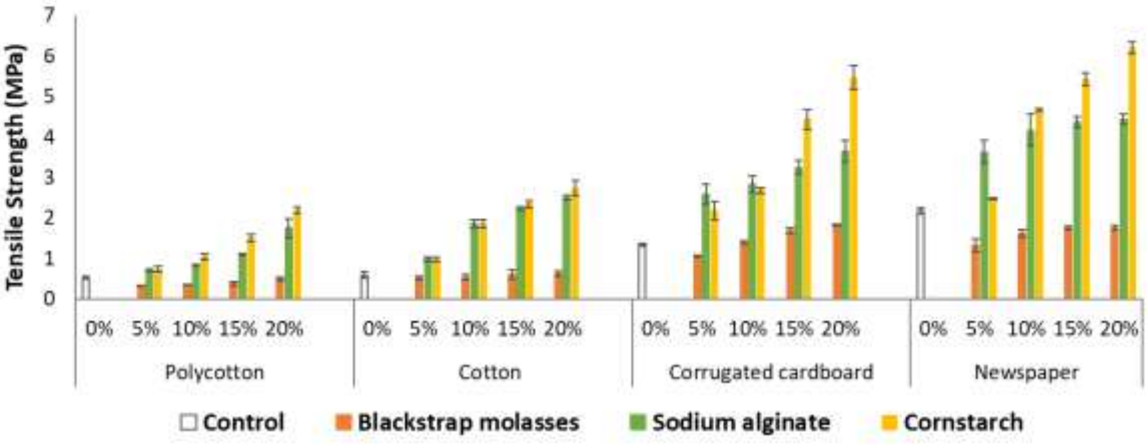


Figure 2.15. Tensile strength of substrates using different binders
(Error bars indicate standard error of the mean)

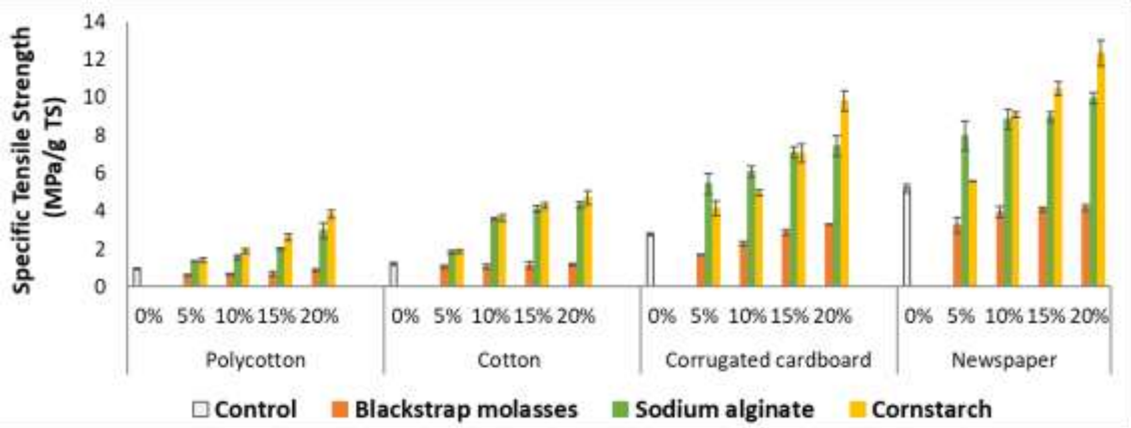


Figure 2.16. Specific tensile strength of substrates using different binders
(Error bars indicate standard error of the mean)

To quantify the extent of increase in tensile strength and specific tensile strength as influenced by the binder addition, the percent increase was calculated by using control (0% binder) as a reference. Figures 2.17 - 2.18 depict the percent increase in tensile strength and specific tensile strength, respectively, to show the effect of using different binders on the substrates. A direct correlation is typically found between the binder concentration and the tensile strength for cornstarch and sodium alginate binders (Chen et al., 2014). However, blackstrap molasses binder was incompatible with the substrates as there was no increase in the tensile strength on all the substrates tested. Moreover, cotton and polycotton had lower tensile strength compared to newspaper and corrugated cardboard as discussed above, the highest percent increase in tensile strength of 395% and 320% were obtained by cotton and polycotton, respectively, at 20% cornstarch binder. In addition, a corresponding increase in terms of specific tensile strength of 325% and 295% were obtained for cotton and polycotton substrates. In the case of corrugated cardboard and newspaper, 20% cornstarch binder led to the highest increase in tensile strength of 310% and 185% and the corresponding increase in specific tensile strength of 250% and 135% were achieved, respectively. For sodium alginate binder, 20% concentration resulted in an optimum tensile strength for all the substrates tested. The results show a tensile strength increase of 325%, 235%, 175% and 105%

and specific tensile strength increase of 260%, 205%, 165% and 90% for cotton, polycotton, corrugated cardboard, and newspaper sheets, respectively.

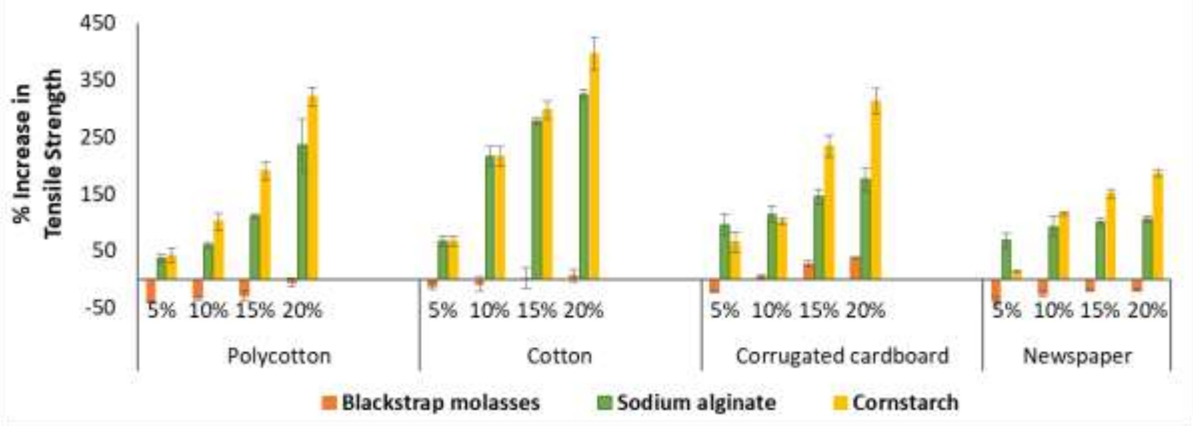


Figure 2.17. Percentage increase in tensile strength using different binders
(Error bars indicate standard error of the mean)

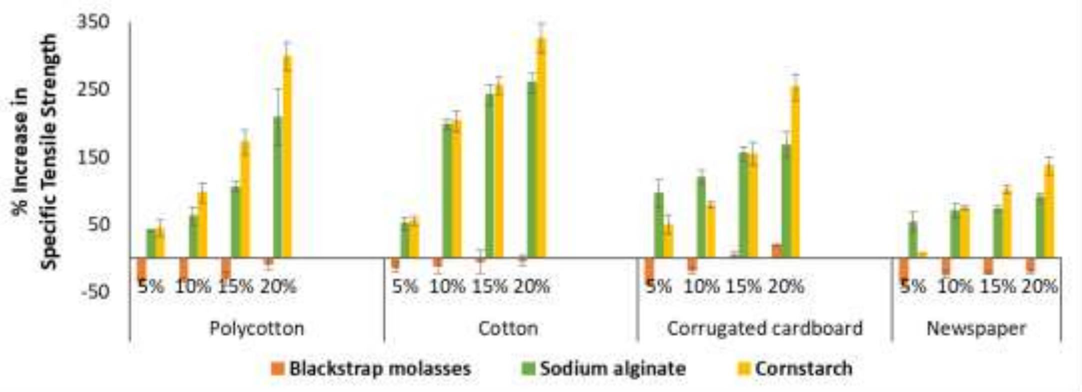


Figure 2.18. Percentage increase in specific tensile strength using different binders
(Error bars indicate standard error of the mean)

2.5 Conclusions

The effect of alkali treatment, compressive load, drying, and binding agent on the tensile strength of homogeneous sheets of cotton, polycotton, newspaper and corrugated cardboard were determined. This study shows that soaking the sheets at 5% NaOH for 5 h obtained an optimum increased in tensile strength by 21%, 19%, and 14% for cotton, newspaper and polycotton, respectively. However, the tensile strength of corrugated cardboard sheets was not enhanced by alkali treatment. Therefore, alkali treatment is an appropriate step for increasing the tensile properties of cotton, polycotton and newspaper substrates, but it is not the same for corrugated cardboard. Moreover, increasing the compressive load from 200 N to 500 N in forming sheets show an improved tensile strength of 12%, 25%, 37% and 42% for corrugated cardboard, polycotton, cotton and newspaper, respectively. Furthermore, an optimum temperature of 105°C for a duration of 5 h for drying the sheets had the highest tensile strength for all substrates. Importantly, the addition of binders show a significant effect on the tensile strength of the sheets, particularly with the use of 20% cornstarch on a dry weight basis per sheet, which increased the tensile strength by 395%, 320%, 310%, and 185% for cotton, polycotton, corrugated cardboard, and newspaper sheets, respectively. An optimum tensile strength of 2.19 MPa, 2.93 MPa, 5.47 MPa, and 6.20 MPa with its corresponding specific tensile strength 3.83 MPa/g TS, 5.10 MPa/g TS, 9.82 MPa/g TS, and 12.31 MPa/g TS for polycotton, cotton, corrugated cardboard, and newspaper sheets were found, respectively. The higher tensile strength of newspaper and corrugated cardboard imply their potential as substrates to be blended with textiles waste of lower tensile strength. It is expected that the optimum results obtained from this study will be useful for the future utilization of the waste substrates as biodegradable containers.

Chapter 3: Development of Biodegradable Seedling Pots from Discarded Textile and Paper Waste

3.1 Abstract

This study evaluates the efficacy of using textile waste blended with paper waste to form biodegradable seedling pot. An optimum blend of substrates with improved tensile and bending strength properties was utilized. A bio-composite blend of cotton (20% cotton, 40% newspaper, and 40% corrugated cardboard) and polycotton (20% polycotton, 40% newspaper, and 40% corrugated cardboard) with an optimum strength were formed into seedling pots. The appreciated seedling pots (untreated blends of cotton and polycotton) were compared with the commercial pots (cardboard seed starter pot and Jiffy pot) in terms of mechanical properties (tensile strength and compressive strength), biodegradability (soil burial test and anaerobic digestion), and seed germination. The untreated blends of cotton and polycotton pots demonstrated a comparable optimum strength, while the Jiffy pot and cardboard seed starter pot obtained the least tensile and compressive strengths, respectively. The anaerobic biodegradability assay suggests that the cotton blend pot, polycotton blend pot, and cardboard seed starter pot can degrade anaerobically because of its high biogas and methane generation potential. Furthermore, the soil burial test result relates with the anaerobic degradability assay. A 100% seed germination was observed from the four seedling pots tested. Thus, the results demonstrated the efficacy of utilizing textile waste to develop seedling pot with desirable strength and biodegradability compared to the commercial seedling pots that can be used for transplanting.

3.2 Introduction

The principle of sustainable development in fostering the utilization of renewable waste materials into an ecologically valuable item led to the notion of developing a biodegradable seedling pot from discarded textile and paper waste. Staggering consumerism and economic growth have generated unsustainable amount of discarded textile and paper waste in municipal solid waste that ends up in landfills. Furthermore, the global expansion of textile industry along with affordability, wide assortment, short life cycle of textile products, and the consumers' fast fashion trend makes clothing disposable but it generates a massive amount of textile waste (Claudio, 2007; Wang, 2010; Lin, 2012; Bukhari & Carrasco-Gallego, 2018). According to WTO (2018), almost 6% of the world's export of manufactured goods in 2017 comprised clothing and textiles. Cotton and polyester are the two predominant fibers in the world (IHS Markit, 2019). Moreover, the dominant role of polyester and cotton in the fiber demand growth has already been established (Textile World, 2015). The global fiber use constitutes of 40% cellulosic and 60% synthetic component (i.e. polycotton) (GFA & BCG, 2017). In 2015, the U.S. generated 16.03 MT (million tons) of textile waste, equivalent to 6.11% of the total MSW, where 65.7% (10.5 MT) were landfilled (USEPA, 2018). Primarily, the textile waste in MSW comprise discarded clothing including non-durable goods such as sheets and towels. Moreover, paper and paperboard waste represent the largest fraction of the total MSW generated (68.05 MT) and recycled (45.32 MT) in the US, but it was the 3rd largest fraction of MSW (18.30 MT) disposed in landfills (USEPA, 2018). This study offers an environmentally sustainable option in diverting textile and paper waste from landfills by converting them into biodegradable seedling pot. Specifically, this study determines an optimum blend of cotton and polycotton with paper waste (newspaper and corrugated cardboard) in terms of tensile and bending strength properties. Also, treated and untreated optimum blends of cotton and polycotton bio-composite sheets were evaluated in terms of tensile and bending strength properties. Furthermore, the resulting desirable untreated blends of cotton and polycotton bio-composite sheets were developed to form biodegradable seedling pots and compared with the two commercially available seedling pots found in the market (cardboard seed starter pot and Jiffy pot) in terms of mechanical properties (tensile strength and compressive strength), biodegradability (soil burial test and anaerobic digestion), and seed germination. This study is beneficial in fostering the sustainable development goals on waste resource recovery, recycling, and utilization.

3.2.1 Alternative containers

Alternative containers or bio-containers were developed to promote sustainable greenhouse and nursery production that addressed the consumers' "green" product perception and environmental sustainability. Bio-containers are made from biodegradable materials, mainly from plant-derived materials, to provide alternative seedling pots by replacing the non-renewable plastic containers. Although, plastic nursery containers have been traditionally used in greenhouse and nursery production due to its agility, reliability, and flexibility. In addition, they are popular to growers, lightweight, durable, and can be reused or recycled. However, the use of plastic container was deemed unsustainable because of its non-biodegradable nature that elevates the pollution load at landfills where most of the plastic is disposed. Used horticulture plastic containers create problems for disposal, and are unsanitary for recycling or reusing due to pre-sorting requirement that limits access to recycling centres, the need of sanitizing or washing of container due to chemical and organic matter contamination, high collection labour cost, and container disintegration due to photo degradation. Furthermore, nursery and greenhouse production practices that avoid plastic use can increase consumer interest. The property of bio-container to degrade naturally when planted or composted attracts marketability that easily distinguishes bio-containers from their unsustainable plastic counterparts (Nambuthiri et al. 2015). Bio-containers can be classified into plantable and compostable pots based on their usage requirement and degradation rate (Evans & Hensley, 2004; Evans et al., 2010).

3.2.1.1 Plantable bio-containers

Plantable bio-containers are planted directly in the ground, which eliminates the need to remove the pot before planting. Once planted, the pot can be easily broken down and allow the roots to penetrate and pass through the container walls into the surrounding soil to eliminate root damage and transplanting fatigue, which helps the survival rate of plants and enhance plant growth (Khan et al., 2000). The factors that determine the pot biodegradation rate includes the nature of container material, soil quality (nutrients, moisture, pH, temperature, and microbial community), and climatic condition (Nambuthiri et al., 2015). Though, plantable containers can be rapidly decomposed, yet they are durable enough for short-term production to withstand watering and handling requirements. The most common plantable containers are made from a combination of peat and wood pulp or paper fibers (Cypher & Fulcher, 2015). Moreover, the plantable containers can reduce transplanting expenses, eliminate disposal of containers, and avoid the use of disposable plastics.

Beeks & Evans (2013) reported the common types of plantable bio-containers available in the market. CowPots (CowPot Co., Brodheadsville, PA) are made of composted, compressed cow manure. Peat pots (Jiffy products, Kristiansand, Norway) are made from peat and paper fiber. Paper pot (Western Pulp Products, Corvallis,OR, and Kord Products, Lugoff, SC) are made from paper pulp. Rice straw containers (Ivy Acres, Inc., Baiting Hollow, NY) are made of rice straw and coconut fiber. Wood fiber containers consist of cedar fibers, peat, and lime (Fertil International, Boulogne Billancourt, France). Coconut fiber containers are made from the medium and long fibers extracted from coconut husks (ITML Horticultural Products, Brantford, Ontario, Canada).

3.2.1.2 Compostable bio-containers

Unlike plantable containers, compostable bio-containers are not designed to be planted with the plant, instead the pot should be removed from the plant before transferring into the final container, field or planting bed, and the used containers are composted separately (Evans et al., 2010). Compostable containers do not degrade quickly and the pot walls are strong enough to hinder the establishment of roots (Beeks & Evans, 2013). For this reason, containers must be removed before planting to be composted in a proper compost pile or composting facility to allow complete decomposition in a relatively short time (Mooney, 2009).

Compostable containers are made from renewable materials that will degrade when the plant is removed. According to Beeks & Evans (2013), one common type of compostable container is made from rice hulls (Summit Plastic Co., Tallmadge, OH). These containers can be also made from a combination of rice hulls, PLA (polylactic acid), recycled paper and/or cardboard. There is a growing interest in compostable containers made from natural fiber waste products such as bamboo and poultry feathers. Because of the vast array of container materials, some bioplastic containers are required to be industrially composted to enhance degradation rate due to slow degradation rates under normal composting conditions (Nambuthiri et al., 2015). ASTM (2004) has set standards for the certification of materials used for industrially composted plastics in the United States wherein bioplastic containers must degrade at least 60% within 90 days of composting period at a temperature of at least 60°C.

3.2.2 Recent studies on bio-containers

Biodegradable pots are produced worldwide and are already being used in many greenhouse and nursery production. However, the development of bio-containers have been progressively focused on utilizing the appropriate biodegradable waste materials, improving the strength of container, and increasing its biodegradability. In one such study, Schettini et al. (2013) utilized recycled wastes of tomato and hemp fibers with sodium alginate as a binder to produce pots for transplanting and found an enhanced development of roots and growth of plants. Stone (2017) utilized biosolids from wastewater treatment facility to develop a biosolids blend of cardboard and cellulose fiber with starch as a binder demonstrated that biosolids had enhanced the plant growth. In a different study, Jirapornvaree et al. (2017) evaluated the suitability of pineapple waste for biodegradable pots and obtained an optimum ratio of pineapple waste (coarse texture) to binder (1:0) with a pot thickness of 1 cm that decomposed after 45 days with a nitrogen and phosphorus release of 0.34% and 7.97 mg-P/kg, respectively. Yamauchi et al. (2006) utilized sweet potato distillation residues with waste newspaper to make recycled pots and observed that the plants' roots penetrated through the pot without causing damage to the plant and the pot served as a fertilizer to the plant upon decomposition. Mohd Rafee (2019) studied the biodegradability of seedling pot made from biomaterials and banana peels suggested that the higher content of banana peels (70%) could accelerate the decomposition of pot. Liew & Khor (2015) investigated the degradability through weight loss of bioplastic pot blended with newspaper pulp fibres and demonstrated that the pots tested below ground had higher percentage of weight loss than those planted above. Also, this study shows that the blended pot of 75% bioplastic and 25% newspaper tested below ground obtained the highest weight loss of 78% after 60 days. Bio-containers blended with valuable components that could enhance plant growth by slow release fertilizer and/or with soil conditioning effect, fungicides, insecticides and plant growth regulators are still being investigated (Nambuthiri et al., 2015). According to Schader (2016), a fertilizer or soil conditioning effect during the pot decomposition is an added beneficial property of a seedling pot. Thus far, in terms of waste materials utilization, there was no available studies have been conducted on developing biodegradable seedling pot using textile waste (cotton and polycotton).

3.3 Materials and Methods

This section involves the discussion on the preparation of bio-composite sheets and bio-composite pots and the tests performed to determine an optimum substrate formulation. The appreciated seedling pots (untreated blends of cotton and polycotton) were compared with the commercial pots (cardboard seed starter pot and Jiffy pot) in terms of mechanical properties (tensile strength and compressive strength), biodegradability (soil burial test and anaerobic digestion), and seed germination.

3.3.1 Preparation of bio-composite sheets

The bio-composite sheets were prepared from different blends of cotton and polycotton with paper waste. From the former study (see Chapter 2), homogeneous sheets of newspaper and corrugated cardboard were found to have higher tensile strength compared to cotton and polycotton. Hence, it is worth blending paper waste with textile waste to improve the strength of the resulting bio-composite sheet. An optimum method using 5% NaOH treatment with 5h soaking, binding rate of 20% cornstarch (dry mass basis), compressive force of 500 N, and drying the sheets at 105°C for 5 h were utilized to form a bio-composite sheet (see Chapter 2). Table 3.1 presents the composition of different blends of cotton and polycotton. Blend 1 consists of 20% textile waste (cotton or polycotton), blend 2 comprises 50% textile waste (cotton or polycotton), and blend 3 consists of 80% textile waste (cotton or polycotton). The remaining concentration for each blend was divided equally into newspaper and corrugated cardboard. Each substrate for a blend was weighed accordingly followed by alkali treatment using 5% NaOH for 5 h soaking, while the corrugated cardboard substrate was soaked in deionized water for 5 h. After the treatment, the cotton, polycotton, and newspaper substrates were rinsed using tap water until it reached a pH of 7. Then, the substrates were blended into pulp and squeezed to remove excess water as described in section 3.3.1. A freshly prepared binder (20% cornstarch) was added into the blended pulp and weighed accordingly so that each sheet prepared for tensile strength and bending strength tests should have 0.5 g TS and 1.3 g TS, respectively.

Table 3.1. Composition of bio-composite sheets

Bio-composite sheets	Substrate composition		
Cotton blend	Cotton	Newspaper	Corrugated cardboard
1	20%	40%	40%
2	50%	25%	25%
3	80%	10%	10%
Polycotton blend	Polycotton	Newspaper	Corrugated cardboard
1	20%	40%	40%
2	50%	25%	25%
3	80%	10%	10%

The resulting blended pulps were formed into two sheets of different sizes to test the tensile and bending strengths. The bio-composite sheet was formed using 5 cm x 2.5 cm and 12 cm x 2.5 cm molds for tensile strength and bending strength tests, respectively (Figure 3.1). The blended bio-composite pulps were evenly spread into the bottom mold and covered with the top mold to form the compacted sheet. The sheets were compressed by placing the mold on the platform of a universal testing machine (Model 3366 Universal Testing Systems, Instron Corp., Norwood, MA, USA). A load of 500 N was applied to the mold by using a 10-kN load cell at a rate of 10 mm/min (Figure 3.2). The same sheet mold compression procedure as discussed in section 3.3.2 was employed in this study. After the compression, the bio-composite sheet was removed from the mold and dried on an aluminum tray for 5 h at 105°C and kept in the desiccator prior to testing. Six replicates for each blend were prepared and tested. An optimum bio-composite blend was determined in terms of tensile strength and bending strength.

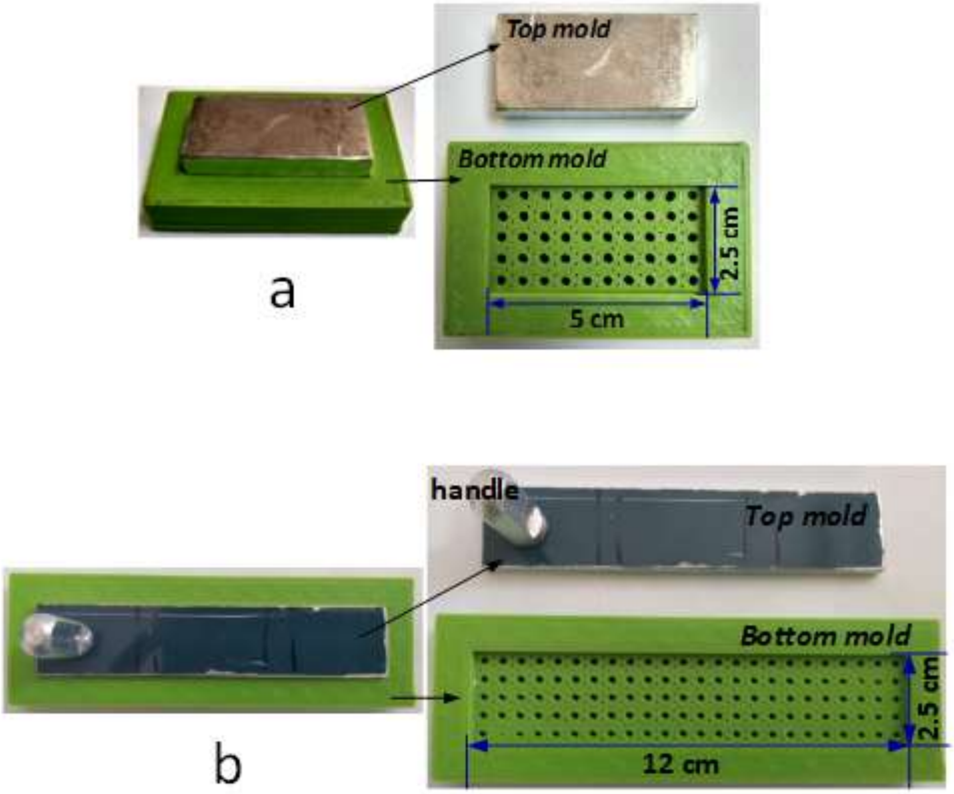


Figure 3.1. Molds for bio-composite sheet for testing the a) tensile strength and b) bending strength

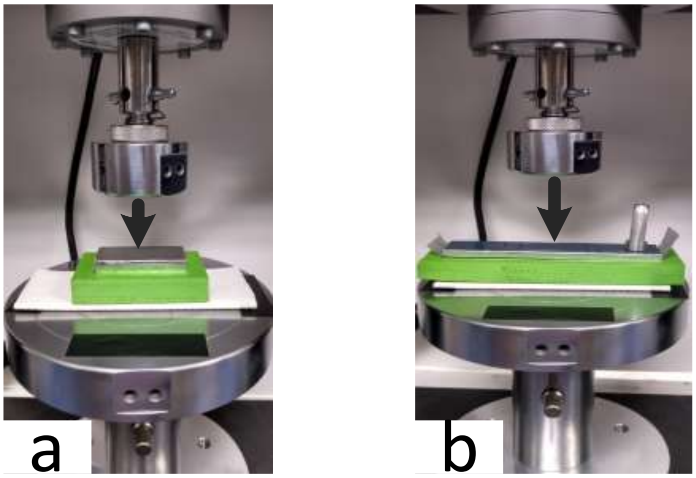


Figure 3.2. Compression set-up to form bio-composite sheet for testing a) tensile strength and b) bending strength

The previous paper (see Chapter 2) shows that an optimum alkali treatment (5% NaOH for 5 h soaking) increased the tensile strength by 14-21% only. However, the addition of binder remarkably improved the tensile strength by 180% up to a maximum of 395%. Herein, the alkali treatment did not significantly enhance the strength of the bio-composite sheet compared to the effect of the binder (20% cornstarch) addition. Therefore, the untreated bio-composite sheets for cotton blend 1 and polycotton blend 1 were considered to compare the tensile strength and bending strength with the treated bio-composite sheets.

3.3.2 Preparation of bio-composite pots

The bio-composite pots were prepared after considering the results of the sequential tests, which determines an optimum strength of bio-composite blends of cotton and polycotton. The untreated bio-composite blends consist of 20% cotton or 20% polycotton, 40% newspaper, and 40% corrugated cardboard to form seedling pots. The average dry mass of the commercial pots (cardboard seed starter pot and Jiffy pot) was 4 g TS per seedling pot and this was used as a reference. Hence, the amount of each substrate corresponds to the percent substrate composition for each blend of cotton and polycotton to ensure that the resulting seedling pot weighs 4 g TS.

The seedling pot was formed using a mold as illustrated in Figure 3.3. The mold was drafted using Solid Works software and created by a 3D printer machine using ABS (Acrylonitrile butadiene styrene) plastic material. Stone (2017) also used the same mold material to form seedling pots discussed the problem of sticking of pot to the mold. To prevent this issue, a layer of polyester cloth was placed at the bottom mold to easily remove the pot and prevent deformation. In addition, the lower portion of top mold was covered with hosiery cloth to easily remove the mold by preventing the sticking of the pot to the mold. The mold was designed to produce a pot having a height of 6 cm, thickness of 0.1 cm, and upper and lower diameter of 6 cm and 4 cm, respectively (Figure 3.4).

Figure 3.3. Mold used to form seedling pot

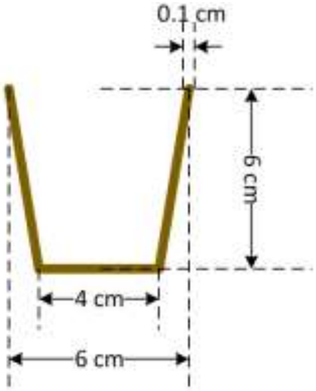


Figure 3.4. Resulting pot dimensions from the mold

The weighed substrate for each blend of cotton and polycotton were soaked in deionized water for 5 h and subjected to hydro-pulping process as described in section 3.3.1. The resulting mixture after binder addition was then manually placed to cover the entire bottom mold. Following that, the top mold was placed atop the bottom mold for compression using a load of 500 N (Figure 3.5). The same compression procedure as described in section 3.3.2 was followed.

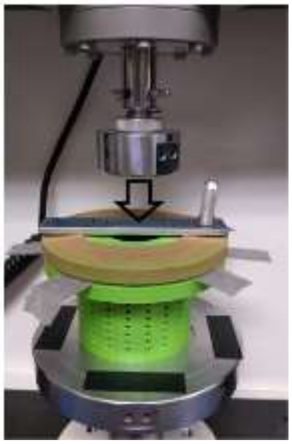


Figure 3.5. Compression set-up to form seedling pot

3.3.3 Mechanical tests

This study determines an optimum bio-composite blend of cotton and polycotton in terms of tensile strength and bending strength tests. The resulting optimum bio-composite blends of cotton and polycotton were used to develop a bio-composite seedling pot. Furthermore, these formulated seedling pots were compared with the commercially available seedling pots (cardboard seed starter pot and Jiffy pot) in terms or tensile strength and compressive strength.

3.3.3.1 Bio-composite sheet

The durability of bio-container is one of the factors considered by the nursery and greenhouse industry prior to utilization (Koeser, 2013). Tensile strength accounts the handling capacity of biodegradable seedling pots (Castronuovo et al., 2015). Typically, tensile forces are exerted on the container walls during plant growth and manually transporting the container (Stone, 2017). A universal testing machine (LS5 Model, Lloyd Materials Testing, Lloyd Instrument Ltd., West Sussex, UK) equipped with 5 kN load cell was used to determine the tensile strength and bending strength of the prepared bio-composite sheets (Figure 3.6). For tensile strength, the top and bottom eccentric roller grips of 50 mm length were attached to the machine that holds the sheet while pulling at a set extension rate (testing speed) of 2 mm/min. The dried sheet with an average dimension of 48 mm x 23.50 mm x 1.20 mm was gripped between the bottom and top roller grips allowing a span length of 15 mm. The bottom grip was kept fixed while the top grip moves upward during tension. The test break detection was enabled to stop the test when the sample breaks. For bending strength, a three-point bending test was used. The sheet with an average dimension of 110 mm x 23.5 mm x 1.20 mm was placed on the bending beam at a span length of 50 mm. The test was performed at an extension rate of 2 mm/min and was set to stop when the sample breaks.

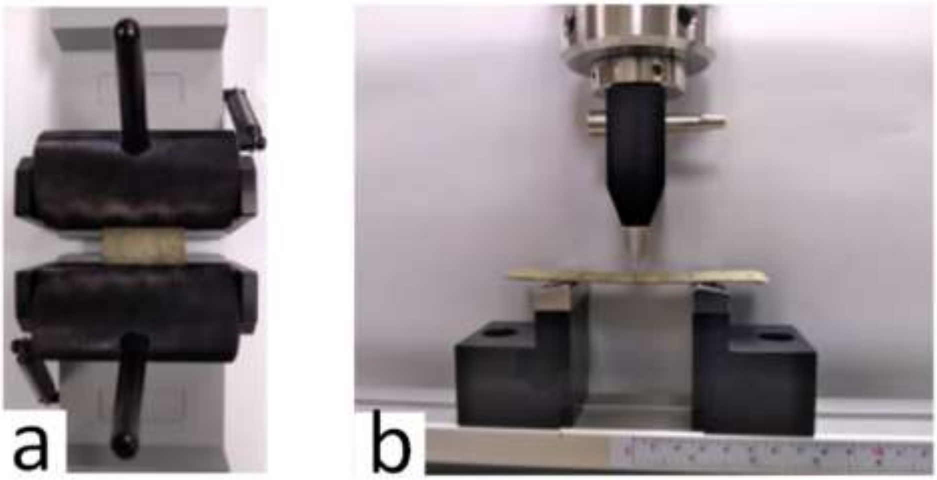


Figure 3.6. Mechanical tests performed on bio-composite sheets a) tensile strength and b) bending strength

3.3.3.2 Seedling pot

The results as discussed in section 3.4.2 were appreciated for untreated bio-composite sheets of cotton and polycotton blends. Tensile strength and compressive strength tests were also performed for cardboard seed starter pot and Jiffy pot to compare the mechanical strength between the formulated seedling pots and the commercial pots. Sheets with the dimensions 5 cm x 2.5 cm were cut from the walls of the Jiffy pot and cardboard seed starter pot for tensile strength test. In addition, compressive strength test was performed on the seedling pots to determine the pot capacity to withstand compression load that can be exerted by the seedling roots along the walls of the container during plant growth. Figure 3.7 shows the tests performed on the studied pots.

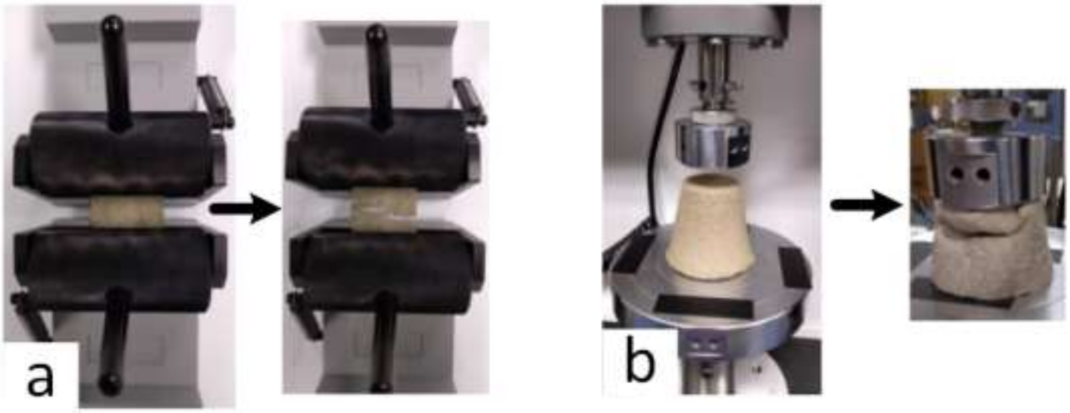


Figure 3.7. Mechanical tests performed on pots: a) tensile strength and b) compressive strength

3.3.4 Degradability test

Degradability is one of the primary factors that determines the bio-container suitability as plantable or compostable. However, there is no existing standard set for testing the bio-container degradation in soil (Briassoulis & Mistriotis, 2014) and to also to distinguish between plantable and compostable bio-container degradation. However, the French national standard offers specification for the biodegradability of bio-based products in soil (Briassoulis & Mistriotis, 2014). The ASTM D6400 is used to certify the industrially compostable plastics in the United States, wherein it must be at least 60% degraded within 90 days at ≥ 60°C (ASTM, 2004). The rate of biodegradation mainly depends on the material type (polymer chemistry) and the environmental factors including the microbial community, moisture content, temperature, pH, and availability of oxygen (Van der Zee et al., 1995). Both anaerobic degradability and soil burial test were performed on the studied seedling pots.

3.3.4.1 Anaerobic degradability test

The anaerobic degradability of optimized bio-composite pots (the untreated cotton blend and polycotton blend) along with the two commercially available pots (cardboard seed starter pot and Jiffy pot) were investigated. This test determines the biodegradability as a measure of specific methane yield and biogas yield, % COD reduction, and % VS reduction. The seedling pots were cut into smaller pieces and further size reduction was performed using a kitchen coffee grinder. Next, the ground pot as substrate was weighed and inoculum was added to attain the substrate to inoculum ratio (SIR) of 0.5 (Table 3.2). The solid analysis of the studied seedling pots is presented in Table 3.3. SIR is one of the important parameters that affects the process stability of anaerobic digestion and the volatile solids concentration of inoculum should always be high compared to that of the substrates (Neves et al., 2004). In one study, Yoon et al. (2014) reported that the SIR should be above 0.1. Furthermore, Juanga-Labayen & Kadir (2019) studied the effect of different SIR of 0.5, 1, 1.5, and 2 using cotton substrate and revealed that the SIR of 0.5 has the highest biogas and methane yields and increasing the SIR over 0.5 can negatively affect the anaerobic digestion performance. Therefore, SIR of 0.5 was used to ensure the high concentration of volatile solids in inoculum as compared to that of the substrates. Blank reactors containing inoculum and deionized water with a resulting concentration of 5 g VS/500 mL were included as control to determine the biogas and methane yields from the inoculum. The background methane produced from the blank assays is subtracted from the methane generated from the substrate (Angelidaki et al., 2009). In this study, the corrected biogas and methane yields (from the substrate) were obtained from the difference between the mean value of biogas and methane yield of the blank reactors and the reactors with SIR of 0.5. The digestion time of 20 days was considered as there was no significant methane production observed in the reactors.

Table 3.2. Volatile solids of substrate and inoculum

Substrate	Substrate (g)	Substrate (g VS)	Inoculum (ml)	Inoculum (g VS)	Volume of water added and substrate (mL)	Total Volume (mL)	Total load (g VS)
Cotton blend pot	2.71	2.5	455	5	45	500	7.5
Polycotton blend pot	2.72	2.5	455	5	45	500	7.5
Cardboard pot	3.09	2.5	455	5	45	500	7.5
Jiffy pot	2.75	2.5	455	5	45	500	7.5
Blank	0	0	455	5	45	500	5.0

Table 3.3. Solid analysis of seedling pot for anaerobic digestion

Substrate	Moisture content (%)	Total solid (%)	Volatile solid (%)
Cotton blend pot	4.11	95.89	95.60
Polycotton blend pot	4.20	95.80	95.80
Cardboard pot	3.53	96.47	83.94
Jiffy pot	6.18	93.82	96.90

Sludge from the anaerobic digestion process is a widely used inoculum for anaerobic biodegradability assay (Owen et al., 1979). In this study, a mesophilic anaerobic inoculum in the form of digested sludge was obtained on 25 June 2019, and it is estimated to be at 12-15 days solid retention time (SRT) from the North End Water Pollution Control Centre (NEWPCC), Winnipeg, Manitoba, Canada. The sludge was pre-incubated at 37°C for two days to be degassed as described by Angelidaki et al. (2009). The inoculum was transferred into the anaerobic vessels via plastic tubing to reach the bottom part of the vessel whilst minimizing air entrapment to maintain the anaerobic condition. The physico-chemical characteristics of the degassed inoculum includes TS of 18,906.33 mg/L, VS of 10,999.33 mg/L, COD of 16,402.62 mg/L and pH of 7.69. Figure 3.8 depicts the anaerobic digestion set-up using a research respirometer equipment (AER 800, Challenge Technology, Arkansas, USA). The anaerobic respirometer was equipped with an enclosed water bath chamber with a temperature controller and thermostat to maintain a mesophilic (37°C) temperature. The water bath chamber has a built-in magnetic stirrer and the stirring mechanism was set at 130 rpm throughout the study. Also, the respirometer was coupled with a computer that automatically recorded the daily biogas production from each digester. A total of 15 Wheaton laboratory glass bottles (Sigma-Aldrich, Ontario, Canada) with a total volume of 775 mL and a working volume of 500 mL were used as digesters. The digesters were filled with inoculum and substrate at SIR of 0.5 in triplicates. To determine the endogenous gas production by the mesophilic anaerobic inoculum, blank bottles were prepared in triplicates without substrate addition but with the same amount of anaerobic inoculum. The bottles were sealed and flushed with 100% nitrogen gas to provide anaerobic condition. The digesters were continuously monitored to produce biogas until it reached a plateau after 20-day period.

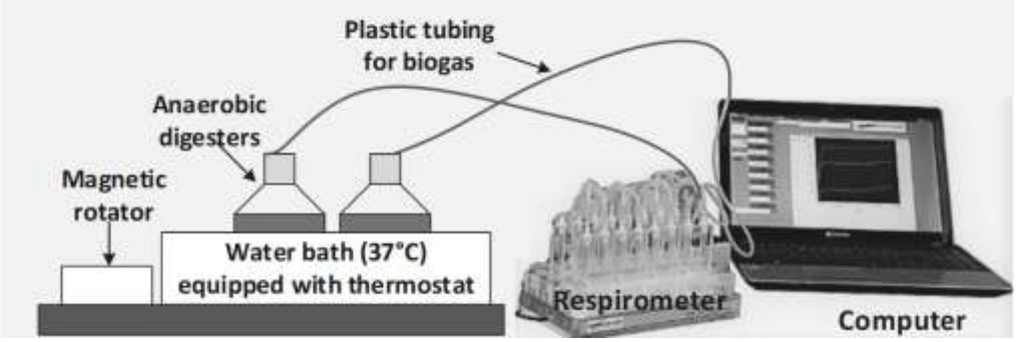


Figure 3.8. Anaerobic degradability assay

3.3.4.2 Soil burial test

The method applied for soil burial study was adapted from SR EN ISO 846/2000, which was also utilized by Vasile et al. (2018) and Popa et al. (2018). This study used a fine grained natural active soil consisting of equal parts of garden soil and compost from yard waste of about 1 kg. The soil was passed through a screen with a mesh size of 2 mm. The soil water content was adjusted to 60 ± 5% by using an aqueous solution of 1 g NH_4NO_3 and 0.2 g K_2HPO_4 per liter of water. The mean pH of soil (20 g soil in 20 mL deionized water) was 7.30, which is within the pH range (6 to 8) set for soil (Mortier & De Wilde, 2014). Samples from the side walls of the seedling pots were cut into 5 cm x 2.5 cm. Samples were weighed using an analytical scale with a precision of 0.0001 g. Four replicates of sheets for each seedling pot were used. Each sample was wrapped using a synthetic net with designated label buried vertically in soil placed in a liter of glass beaker (Figure 3.9). The samples were incubated at a temperature of 25°C for a total of 4 months. At the end of each testing intervals (15 days, 30 days, 45 days, 60 days, 75 days, 90 days, 105 days, and 120 days), the sheet samples were prevailed from the soil, washed with deionized water to remove adherent soil, and dried on paper wipes and stored in the desiccator for at least 48 h until a constant weight can be attained. Sheet samples were weighed at the beginning and at the end of each test interval and the weight loss signifies the degree of degradation. The total % weight loss after 4 months was determined (Equations 3.1 and 3.2).

$$\%\,Weight\ loss = \frac{Initial\ wt.\ at\ day_0 - Final\ wt.\ after\ day_{15}}{Initial\ wt.at\ day_0}\ x\ 100 \qquad (3.1)$$

$$\%\,Weight\ loss_{(after\ every\ 15\ days)} = \frac{Initial\ wt.before\ day_{15} - Final\ wt.after\ day_{15}}{Initial\ wt.\ before\ day_{15}} x100 \qquad (3.2)$$

Figure 3.9. Soil burial test using different seedling pots

3.3.5 Germination test

A seed germination assay was prepared using a saturated aqueous extract of untreated cotton blend pot, untreated polycotton blend pot, cardboard seed starter pot, and Jiffy pot. A saturated aqueous extract from each of the studied seedling pots was extracted using a procedure described by Rhoades (1996). The dried pots were manually cut into smaller pieces, ground using a coffee grinder, weighed, and transferred into a flask. The amount of deionized water added into the flask was 5 times the weight of the pot (1:5). In this study, 40 g of each seedling pot was used, and 200 mL of deionized water was added. Then, the flasks were covered and placed in a mechanical shaker for 1 h. Thereafter, the suspension was filtered using a Buchner filtration set-up. Figure 3.10 presents the extracted aqueous solution from the four seedling pots. Germination testing was performed to determine the toxicity of the studied seedling pots on four different seeds (lettuce, navy bean, soybean, and mung bean) using a procedure described by USEPA (1996). Tests were performed by placing two discs of Whatman qualitative filter paper in a disposable plastic petri dish (100 mm x 15 mm). Ten identical undamaged seeds for each seed variety were spaced out evenly on the filter paper in each dish, which were subsequently wetted with 4 mL of the saturated extract aqueous solution. Triplicates were performed for each seed using four different extract solutions. For each seed variety, a triplicate control dish using deionized water was also included. All dishes were incubated at 25°C for 7 days under dark condition. After 7 days, the seed germination (SG) and the relative seed germination (RSG) were determined (Equations 3.3 and 3.4) (Luo et al., 2018). The seed was considered to be germinated when the length of the primary root became 5 mm (USEPA, 1996).

$$SG = \frac{Number\ of\ germinated\ seeds}{Number\ of\ total\ seeds}\ x\ 100\% \qquad (3.3)$$

$$RSG = \frac{Number\ of\ germinated\ seeds\ (sample)}{Number\ of\ germinated\ seeds\ (control)}\ x\ 100\% \qquad (3.4)$$

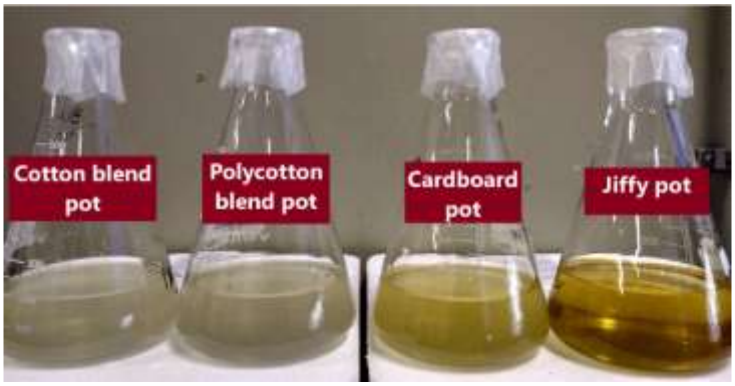


Figure 3.10. Saturated aqueous extract from the studied pots

3.4 Results and Discussion

3.4.1 Tensile strength and bending strength of bio-composite sheet

Figure 3.11 shows the tensile strength of the bio-composite sheets for different blends of cotton and polycotton, wherein the cotton, polycotton, and newspaper were treated using 5% NaOH for 5 h soaking, while the corrugated cardboard was soaked in deionized water for 5 h. Among the three cotton blends, cotton blend 1 achieved an optimum tensile strength of 5.40 MPa with an equivalent specific tensile strength of 9.58 MPa/g TS. The cotton blend 2 and cotton blend 3 attained the lower tensile strength of 4.05 MPa (7.02 MPa/g TS) and 3.85 MPa (6.29 MPa/g TS), respectively. Furthermore, for polycotton blends, the same trend was observed; the polycotton blend 1 achieved an optimum tensile strength of 3.99 MPa (7.23 MPa/g TS) compared to the other blends. The tensile strength result for polycotton blend 2 and polycotton blend 3 were 1.91 MPa (3.27 MPa/g TS) and 1.17 MPa (1.88 MPa/g TS), respectively. Thus, cotton blend 1 and polycotton blend 1 are the optimum blends that achieved the highest tensile strength. It should be noted that these bio-composite sheets consist of 20% textile (cotton or polycotton) waste with 40% newspaper and 40% corrugated cardboard.

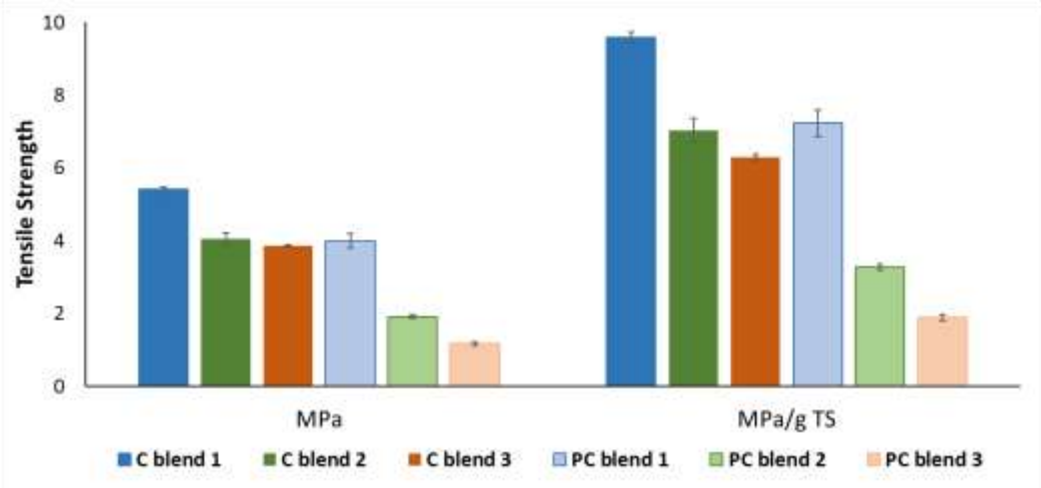


Figure 3.11. Tensile strength of bio-composite blends of cotton and polycotton
(Error bars signifies standard error of the mean; C blend – cotton blend; PC blend – polycotton blend)

Figure 3.12 shows the image of bio-composite sheets subjected to the bending strength test. Figure 3.13 depicts the bending strength results. Among the three cotton blends, the cotton blend 1 achieved an optimum bending strength of 11.34 MPa with an equivalent specific bending strength of 8.44 MPa/g TS. While the cotton blend 2 and cotton blend 3 attained lower bending strength of 8.65 MPa (6.30 MPa/g TS) and 8.33 MPa (5.89 MPa/g TS), respectively. Furthermore, for polycotton blends, the same trend was observed; the polycotton blend 1 achieved an optimum bending strength of 8.22 MPa (5.97 MPa/g TS) compared to the other blends. The bending strength results for polycotton blend 2 and polycotton blend 3 were 3.62 MPa (2.70 MPa/g TS) and 2.81

MPa (2.00 MPa/g TS), respectively. Thus, the cotton blend 1 and polycotton blend 1 are the optimum blends that achieved the highest bending strength. As also observed for the tensile strength results, a bio-composite sheet consisting of 20% textile (cotton or polycotton) with 40% newspaper and 40% corrugated cardboard was the most desirable blend for optimum bending strength.

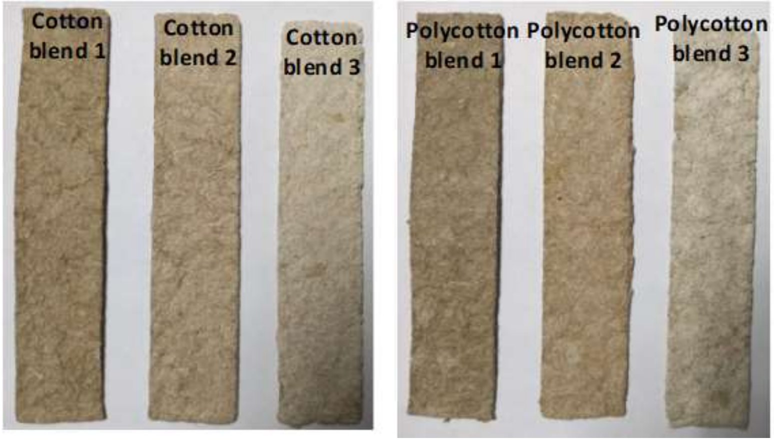


Figure 3.12 Treated bio-composite sheets for bending test

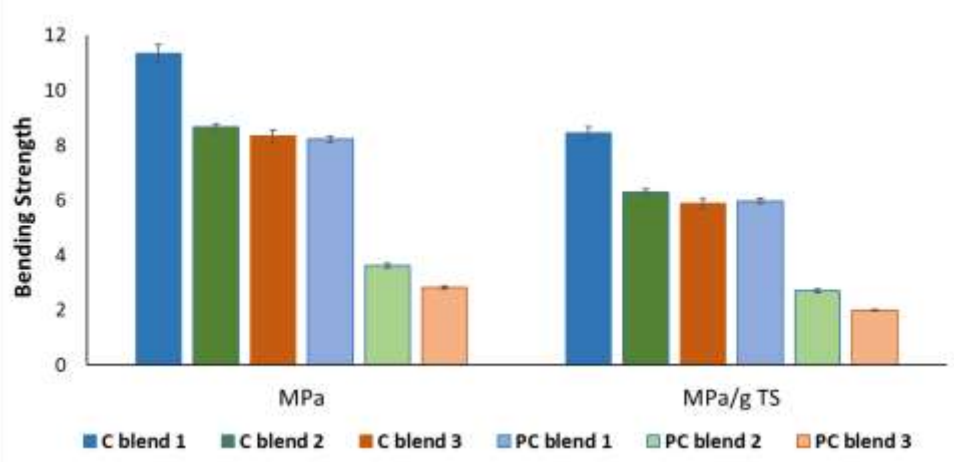


Figure 3.13. Bending strength of bio-composite blends of cotton and polycotton
(Error bars indicate standard error of the mean; C blend – cotton blend; PC blend – polycotton blend)

3.4.2 Tensile strength and bending strength of treated and untreated bio-composite sheets

This study compared the tensile and bending strengths of the optimum blends of cotton and polycotton (cotton blend 1 and polycotton blend 1) with its corresponding blends without alkali treatment. As discussed in Chapter 2, the effect of binder addition (20% cornstarch) significantly affects the tensile strength of sheets compared to the alkali treatment. Figure 3.14 presents the tensile strength results for treated and untreated blends of cotton and polycotton. A comparable tensile strength of 5.40 MPa (9.58 MPa/g TS) for treated and 4.81 MPa (8.62 MPa/g TS) for untreated cotton blends were observed. Also, a comparable tensile strength of 3.99 MPa (7.07 MPa/g TS) and 4.14 MPa (7.33 MPa/g TS) were observed for the treated and untreated blends of polycotton, respectively. Figure 3.15 presents the bio-composite samples subjected to bending test. Figure 3.16 demonstrates the bending strength results. For cotton blends, the bending strength for treated and untreated sheets were 11.34 MPa (8.44 MPa/g TS) and 10.49 MPa (7.79 MPa/g TS), respectively. While, for polycotton blends, the bending strength for treated and untreated sheets were 8.22 MPa (5.97 MPa/g TS) and 7.05 MPa (5.35 MPa/g TS), respectively. Similar values of the tensile and bending strengths for the treated and untreated blends of cotton and polycotton were observed. The result indicates that alkali treatment did not have a significant effect on enhancing the strength of bio-composite sheets made from cotton and polycotton blends. The overlapping of error bars signifies no significant difference between the treated and untreated blends. This further implies that treatment is non-essential in preparation of the seedling pots. The exclusion of alkali treatment in the process provided added benefits of water conservation as rinsing is no longer necessary and thereby minimizing wastewater.

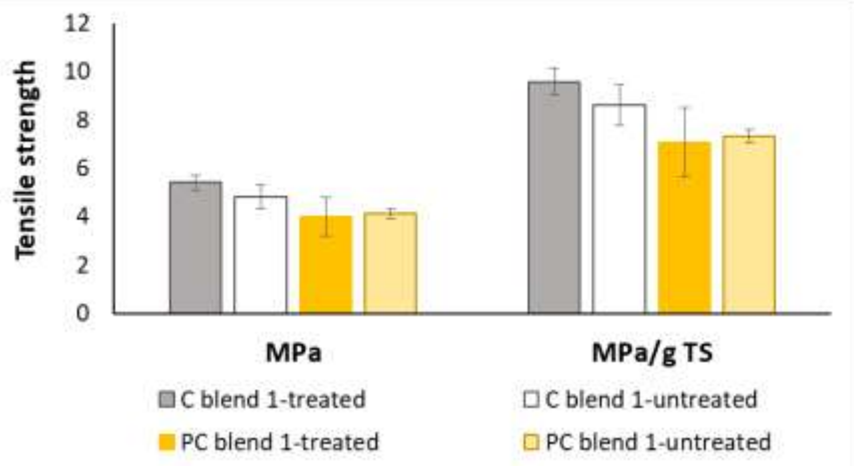


Figure 3.14. Tensile strength of treated and untreated cotton and polycotton blends (Error bars indicate standard error of the mean; C blend – cotton blend; PC blend – polycotton blend)

Figure 3.15. Treated and untreated bio-composite blends of cotton and polycotton for bending test

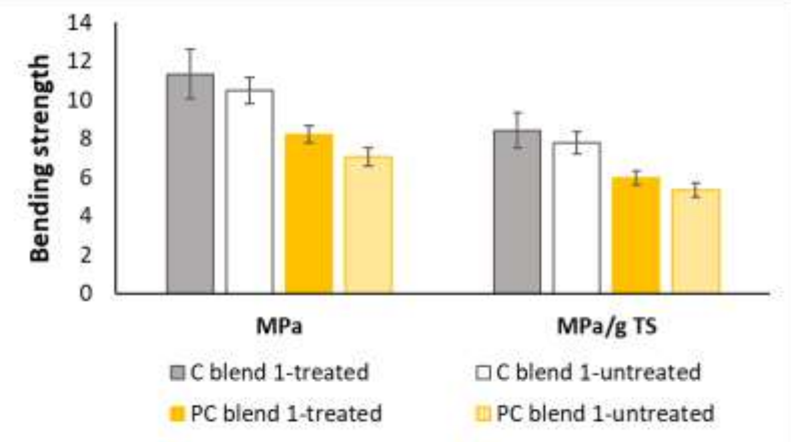


Figure 3.16. Bending strength of treated and untreated cotton and polycotton blends (Error bars indicate standard error of the mean; C blend – cotton blend; PC blend – polycotton blend)

3.4.3 Tensile strength and compressive strength of seedling pots

Comparison of the tensile strength and compressive strength of the two commercially available seedling pots (cardboard seedling pot and Jiffy pot) with optimum blends of untreated cotton and polycotton pots was also carried out in this study. Figure 3.17 shows the tensile strength results of the four seedling pots. The cotton blend pot attained an optimum tensile strength of 4.81 MPa and followed by the polycotton blend pot of 4.14 MPa. While for the commercial seedling pots, the cardboard pot has a tensile strength of 3.74 MPa and the Jiffy pot attained the lowest tensile strength of 2.49 MPa. The specific tensile strength, which considers the strength of the sheet on dry mass basis, follows the same trend as the tensile strength. However, since the cardboard pot was lighter, its specific tensile strength is comparable with the cotton blend pot. The specific tensile strength of cotton blend pot and cardboard pot were 8.62 MPa/g TS and 8.59 MPa/g TS, respectively.

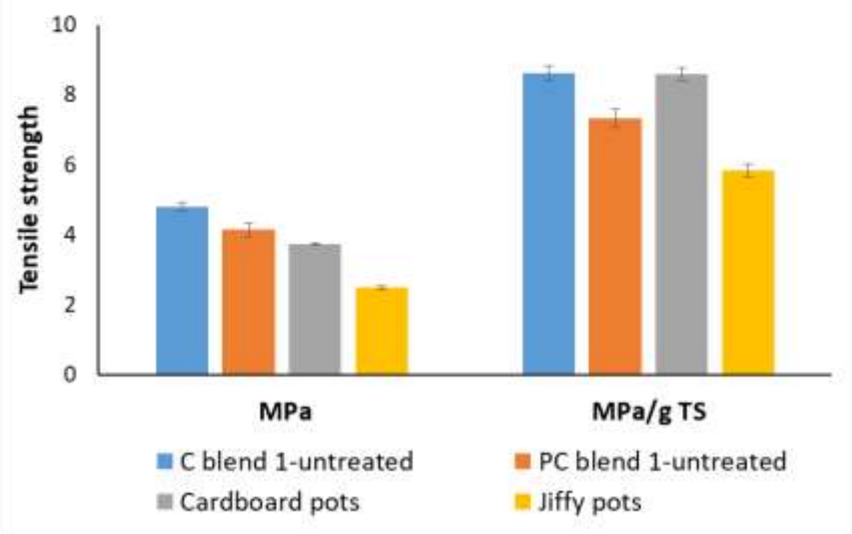


Figure 3.17. Tensile strength of the developed seedling pots and the commercial pots (Error bars indicate standard error of the mean; C blend – cotton blend; PC blend – polycotton blend)

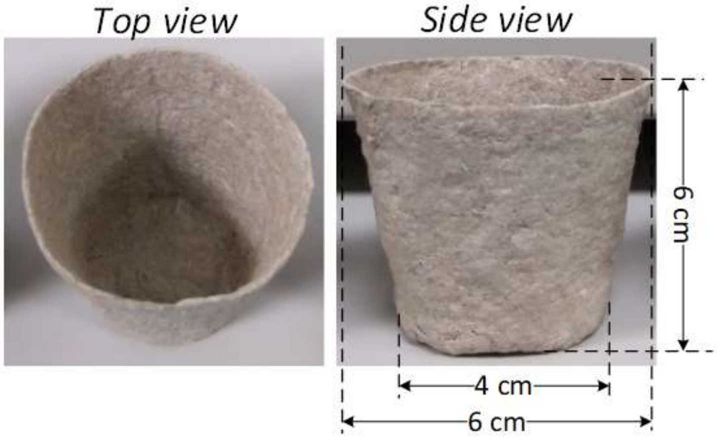


Figure 3.18. Dimension of the resulting pot from the mold

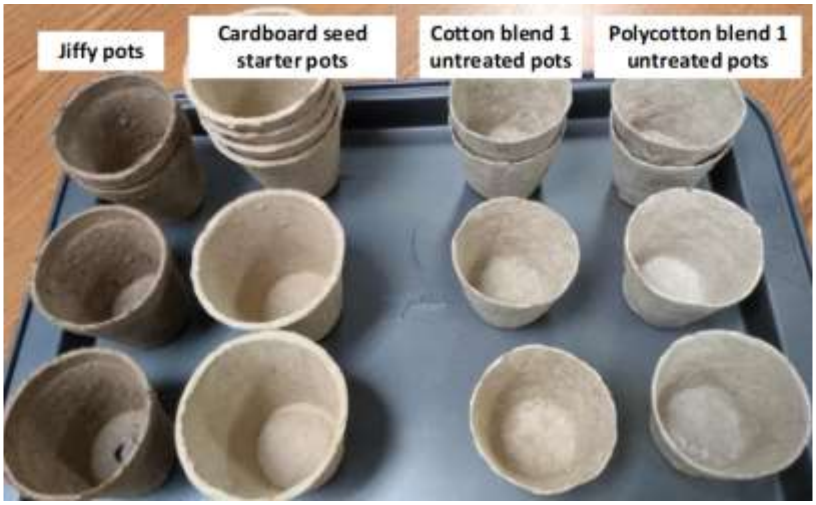


Figure 3.19. Seedling pots for compressive strength test

Figure 3.18 illustrates the dimensions of the pots produced in this study and Figure 3.19 shows different seedling pots before being subjected to compressive strength test. Figure 3.20 presents the maximum compressive load at break for the studied pots. The cotton blend and polycotton blend pots attained the highest compressive strength compared to the two commercial pots considered in this study. The cotton blend pot has the highest compressive strength of 256.64 N, which is comparable with the polycotton blend pot of 236.13 N. The Jiffy pot has higher compressive strength of 202.86 N than the cardboard pot of 163.61 N.

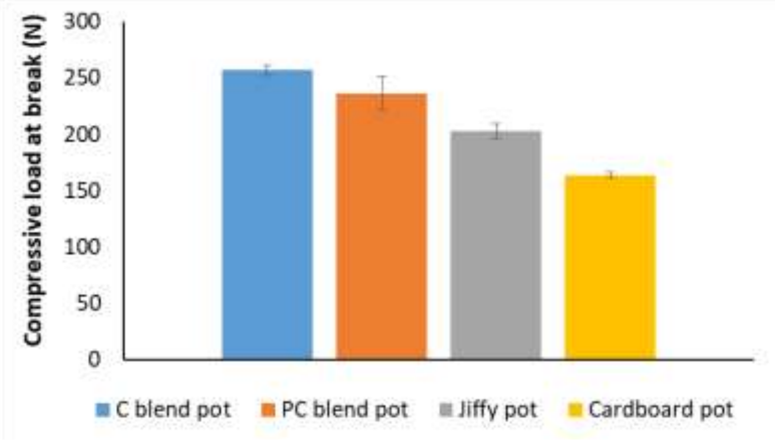


Figure 3.20. Compressive strength of the developed seedling pots and the commercial pots (Error bars indicate standard error of the mean; C blend – cotton blend; PC blend – polycotton blend)

3.4.4 Anaerobic biodegradability of seedling pots

Figures 3.21 - 3.22 present the specific biogas and methane yields for the studied seedling pots, respectively. From the results, the cotton blend pot produced the highest biogas and methane yields of 494.30 mL/ g VS and 271.80 mL/ g VS, respectively. In addition, the polycotton blend pot and cardboard pot generated an appreciable biogas and methane yields compared to the Jiffy pot. Polycotton blend pot has a biogas yield of 426.2 mL/ g VS and a methane yield of 250.94 mL/g VS, while cardboard pot yielded 402.4 mL/g VS and 218.6 mL/g VS of biogas and methane, respectively. It can be deduced that the cotton blend pot, polycotton blend pot, and cardboard pot can degrade anaerobically because of its potential to generate higher yields of biogas and methane. Furthermore, Figures 3.21 - 3.22 illustrate that a shorter digestion period of 10 days is possible to yield optimum biogas and methane production where a sharp plateau can be observed. This implies that the cotton blend pot, polycotton pot and cardboard pot are potential substrates for anaerobic digestion.

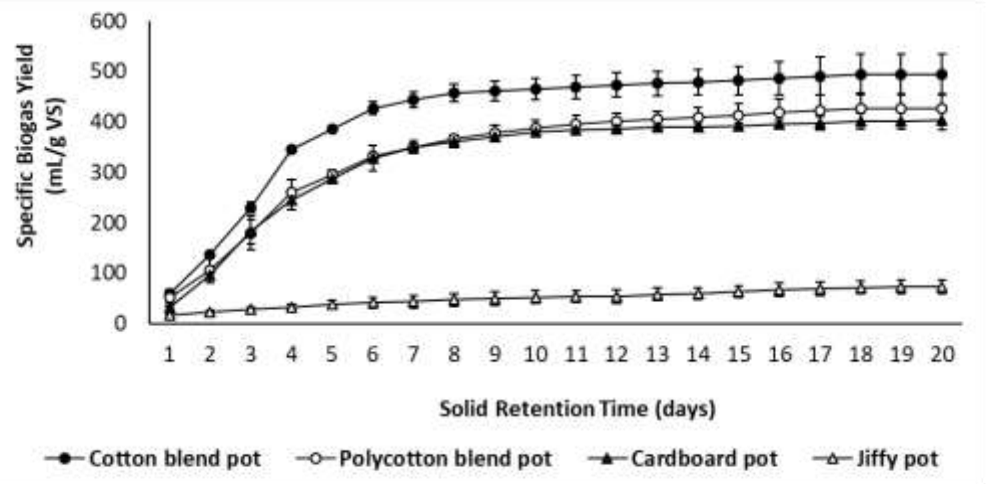


Figure 3.21. Specific biogas yield of seedling pots

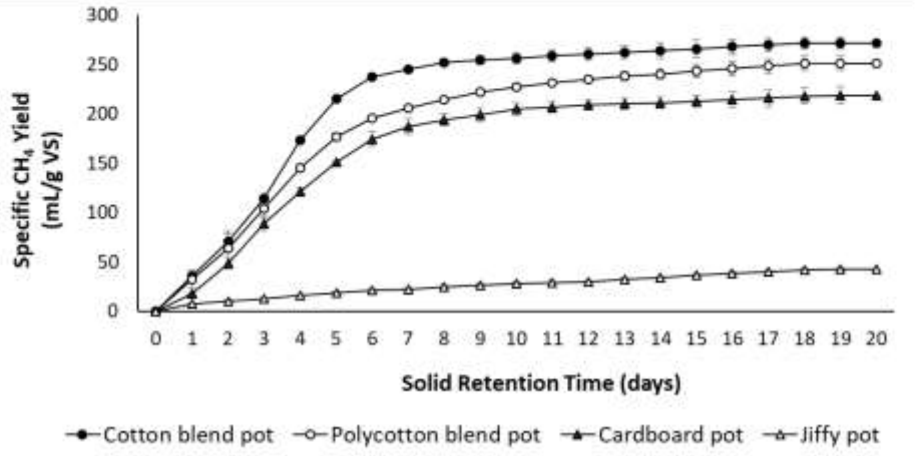


Figure 3.22. Specific methane yield of seedling pots

The anaerobic digestion process using these substrates was stable or there was no inhibition observed during the methane phase. Figure 3.23 presents the methane concentration of different seedling pots including the blank reactors during the digestion period. The methane concentration rose above 50% after 4 days of anaerobic digestion period for all the reactors indicating an active methane phase. According to Juanga et al. (2007), an active methane phase is indicated by at least 50% CH_4 concentration in biogas and a pH of 7.0. Besides methane concentration, the pH is a major parameter used to indicate a stable methane phase as most methanogens are active between pH of 7 and 8 while acidification phase often has a lower pH (Angelidaki & Ahring, 1994; Angelidaki & Sanders, 2004). Therefore, the pH was also measured after the digestion period to determine methane phase inhibition. After 20 days of anaerobic digestion, the pH of the resulting digestates were measured. The measured pH were 7.52, 7.16, 7.23, 7.16 and 7.22 for blank, cotton blend pot, polycotton blend pot, cardboard seed starter pot, and Jiffy pot, respectively. All the aforementioned pH values are above 7 and therefore indicate a stable methane phase. Though, the digester that contains the Jiffy pot substrate show a stable pH condition and methane concentration above 50%, restricted anaerobic degradation was observed because of its lower biogas and methane potential. This can be further explained from the % VS reduction and % COD reduction. Among the seedling pots studied, the Jiffy pot attained the lowest % VS reduction and % COD reduction of 32% and 20%, respectively. This indicates that the Jiffy pot is not easily degraded anaerobically. Interestingly, the % VS reduction for cotton blend pot, polycotton blend pot and cardboard pot were 56%, 51% and 50%, respectively, which compliments with the % COD reduction of 66% for the cotton blend pot, polycotton blend pot, and cardboard pot.

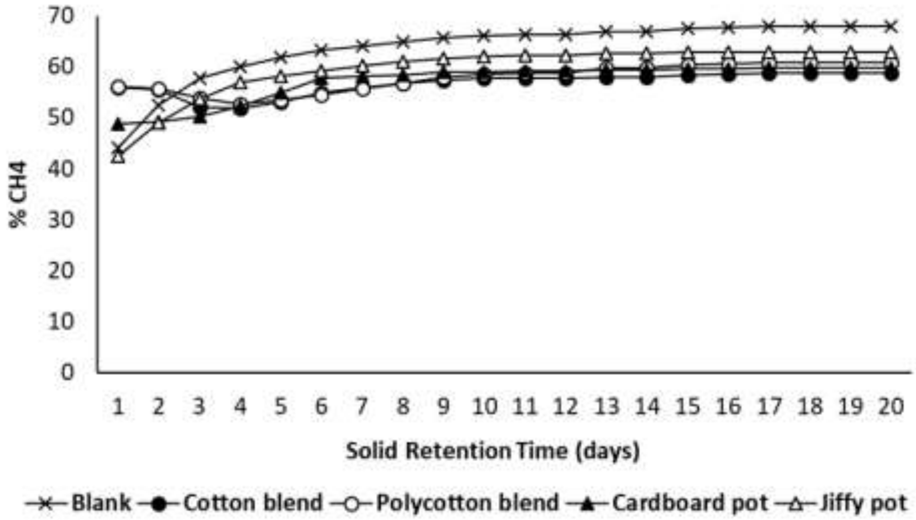


Figure 3.23. Methane concentration of seedling pots
(Error bars indicate standard error of the mean)

3.4.5 Soil burial test

The degree of degradation was determined based on the cumulative percent weight loss of the samples buried in soil as a function of time (Figure 3.24). Generally, it is observed that the cumulative percent weight loss is directly proportional with the number of days. After 120 days, the highest percent weight loss of 80% and 78% were obtained for cotton blend and cardboard seed starter pot, respectively. The polycotton blend shows 64% cumulative weight loss. The polycotton consists of 60% cotton and 40% polyester, which is synthetic and non-biodegradable. However, the desirable weight loss was observed for cotton and polycotton blends and this can be attributed to the presence of cornstarch as a binder. Yahya et al. (2014) demonstrated that the addition of starch into natural rubber latex increased the film weight loss by soil burial test. The Jiffy pot attained the lowest degradability of 16%. The French specification (NF U52-001) defines the criteria for soil biodegradability as a minimum of 60% and a maximum of 90% if soil (for 12-month period) and compost media (for 6 months) are used (Briassoulis & Mistriotis, 2014). This denotes that the cotton and polycotton blend samples and the cardboard seed starter pot meet the French standard for soil biodegradation criteria. However, the Jiffy pot is the least biodegradable among the samples tested, which is required to be tested beyond 4 months of soil burial test. Figure 3.25 presents the percent weight loss at every 15-day interval and shows a significant percent weight loss after 15 days for all the samples. Almost 50% of the weight loss was achieved after 45 days; however, significant weight loss extends until 75 days for the cotton blend. The soil burial test denotes degradability of 80% and 78% for cotton blend pot and cardboard pot, respectively, followed by polycotton blend pot (64%), and the least degradable was the Jiffy pot (16%). The results from the anaerobic degradability test also relates with the soil burial tests.

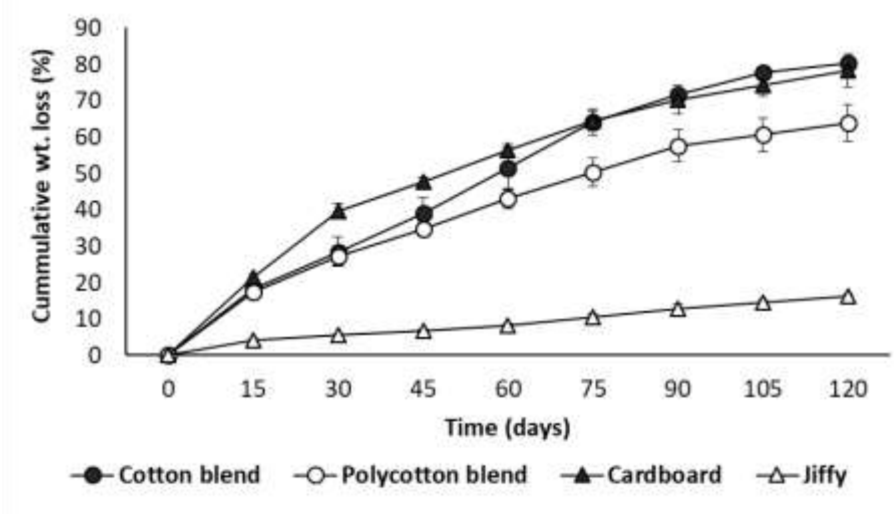


Figure 3.24. Cumulative weight loss of the pots (Error bars indicate standard error of the mean)

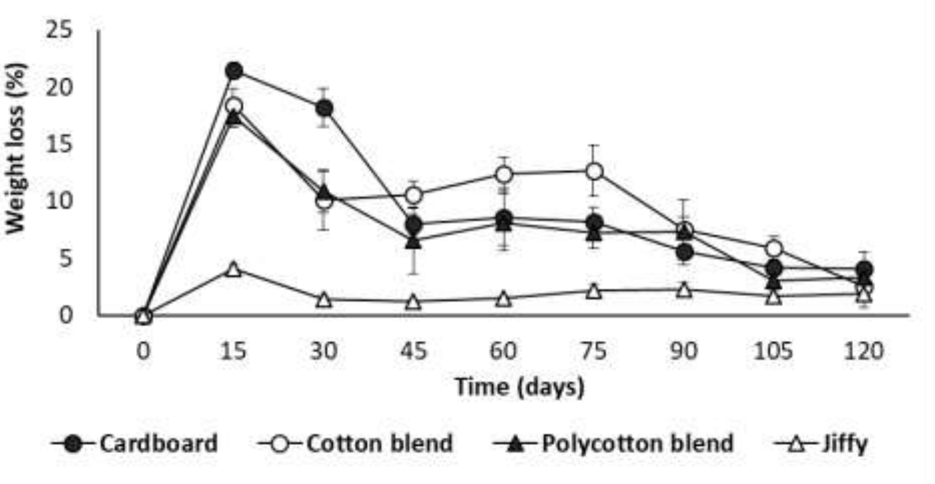


Figure 3.25. Weight loss of studied pots at every 15-day interval
(Error bars indicate standard error of the mean)

3.4.6 Germination test

The pH and conductivity values of the aqueous extracts are shown in Table 3.4. After 7 days of incubating the dishes with seeds, it is observed that the seed germination and the relative seed germination for all the seeds tested from the four saturated aqueous pot extracts were 100% (Table 3.5). Figure 3.26 represents a photograph of the germinated seeds using aqueous extract from the cotton blend pot. This shows that all the seedling pots do not have a toxicity effect on seed germination.

Table 3.4. pH and conductivity of aqueous extracts from studied pots

Aqueous extracts	pH	Conductivity (μS/cm)
Cotton blend pot	7.37	206.30
Polycotton blend pot	7.40	220.20
Cardboard pot	7.39	614.10
Jiffy pot	4.72	236.60

Table 3.5. Seed germination rate results

Seeds	Control	Cotton blend pot	Polycotton blend pot	Cardboard pot	Jiffy pot
Lettuce	100%	100%	100%	100%	100%
Navy bean	100%	100%	100%	100%	100%
Soybean	100%	100%	100%	100%	100%
Mung bean	100%	100%	100%	100%	100%

Figure 3.26. Germination tests of four seeds using cotton blend pot aqueous extract

3.5 Conclusions

This study evaluated the efficacy of utilizing textile waste (cotton and polycotton) blended with paper waste (newspaper and corrugated cardboard) to create a biodegradable seedling pot. The cotton blend pot achieved the optimum tensile strength and compressive strength of 4.81 MPa and 256.64 N, respectively, whereas a comparable tensile strength of 4.14 MPa and compressive strength of 236.13 N were observed from polycotton blend pot. While for the commercial seedling pots, the least tensile strength of 2.49 MPa and compressive strength of 163.60 N were achieved by Jiffy pot and cardboard seed starter pot, respectively. The anaerobic biodegradability assay suggests that the cotton blend pot, polycotton blend pot, and cardboard seed starter pot can be attractively degraded anaerobically because of its higher biogas and methane generation potential. The % VS degradation after 20 days of anaerobic digestion for cotton blend pot, polycotton blend pot, cardboard seed starter pot, and Jiffy pot were 56%, 51%. 50%, and 32%, respectively. The results relate with a 120-day soil burial test; the degree of degradation results for cotton blend pot, cardboard seed starter pot, polycotton blend pot, and Jiffy pot were 80%, 78%, 64%, and 16%, respectively. A 100% seed germination was observed from the four seedling pots tested using lettuce, navy bean, soybean, and mung bean seeds implying that the seedling pots has no toxicity effect on the seed growth. Thus, the results demonstrated that the developed seedling pots obtained an optimum strength and biodegradability compared to the tested commercial seedling pots. It is recommended to further the study for plant growth test to determine the suitability of the pots as compostable or plantable. For future work, it is desirable to utilize agro-industrial waste to be blended with textile waste to develop a nutrient-rich biodegradable seedling pot with fertilizer release on soil upon its degradation.

Chapter 4: Engineering Significance

4.1 Importance of the Research

The expansion of clothing and textile industry along with the changes in consumer fashion trends have caused a rapid increase of textile waste in MSW stream globally. In 2017, textile waste constitutes 6.3% (16.89 MT) of the total municipal solid waste and 66% (11.15 MT) of generated textile waste is landfilled in the US (USEPA, 2019a). The typical textile waste management practices include re-use, recycling, composting, incineration, and landfilling (Hu et al., 2018; Iaquaniello et al., 2017; Nunes et al., 2018; Sandin & Peters, 2018). However, large fraction of textile waste still end up in landfills that is deemed unsustainable. It is indispensable to promote an enhanced diversion of textile waste from landfill. Utilizing unwanted textile along with paper waste to produce a valuable item like seedling pot that is biodegradable can promote not only environmental sustainability but also horticulture sustainability.

Plastic containers for greenhouse and nursery production have been the predominant container type since 1980s (Nambuthiri et al., 2015) and even today. It is because they are lightweight, durable, popular to growers, and can be reused or recycled. However, in reality plastic containers are rarely recycled and typically disposed in landfills, because they are unattractive for recycling or reusing due to pre-sorting requirement that limits access to recycling centres, the need of sanitizing or washing of container due to chemical and organic matter contamination, high collection labour cost, and container disintegration due to photo degradation (Gathe & Kowal, 1993; Helgeson et al., 2009; Hall et al., 2010; Chappell & Know, 2012). The use of plastic container was deemed unsustainable because of its non-biodegradability nature that elevates pollution load at landfills where are mostly disposed.

Alternative containers or bio-containers were developed to promote sustainable greenhouse and nursery production that addressed the consumers' "green" product perception and environmental sustainability. The property of bio-container to degrade naturally when planted or composted attracts marketability that easily distinguishes bio-containers from their unsustainable plastic counterparts (Nambuthiri et al. 2015). Bio-containers are made from biodegradable materials mainly from plant-derived materials that are developed to provide alternative seedling pots replacing the non-renewable plastic containers. Thus, this study was developed to promote textile waste diversion from landfill by using them to produce a sustainable product which can benefit the horticulture production replacing plastic nursery containers and avoiding plastic container waste generation.

4.2 Engineering Significance and Implications

This study explored the optimization process in improving the strength of bio-composite blend of textile waste with paper waste formed into seedling pot that demonstrate the strength, biodegradability potential, and safe for seed germination. The effect of alkali treatment, increasing the compressive force, effect of binder addition, and effect of drying condition on the studied homogeneous substrates were investigated. The findings show that among the treatments performed, the 5% NaOH for 5 h soaking obtained an optimum increase in tensile strength by 21%, 19%, and 14% for cotton, newspaper and polycotton, respectively. However, none of the alkali treatments enhanced the tensile strength of corrugated cardboard. In terms of increasing compressive load from 200 N to 500 N, the results showed an improved tensile strength of 14%, 25%, 37%, and 42% for corrugated cardboard, polycotton, cotton and newspaper, respectively. The favourable optimum temperature of 103°C for a drying duration of 5 h was considered. Remarkably, among the binding agents tested, cornstarch at 20% concentration obtained an increased optimum tensile strength by 320%, 395%, 310% and 185% for polycotton, cotton, corrugated cardboard and newspaper sheets, respectively.

The optimized findings above were employed to sequentially improve the mechanical strength (tensile and compressive strengths) of the bio-composite blend and bio-composite seedling pot. The appreciated seedling pots (untreated blends of cotton and polycotton) that exhibit comparable tensile strength with the treated blends were compared with the commercial pots (cardboard seed starter pot and Jiffy pot) in terms of mechanical properties (tensile strength and compressive strength), biodegradability (soil burial test and anaerobic digestion), and seed germination. The untreated blends of cotton and polycotton pots demonstrate a comparable optimum strengths, while the Jiffy pot and cardboard seed starter pot obtained the least tensile and compressive strengths, respectively. The anaerobic biodegradability assay and soil burial test suggest that the cotton blend pot, polycotton blend pot, and cardboard seed starter pot can be attractively degraded both anaerobically and in soil. A seed germination results (100%) recommend that the studied container pots do not pose risk or toxicity to the growth of seeds. Thus, the results revealed the potential of using textile waste along with paper waste to produce a sustainable horticulture pots.

4.3 Cost Saving in Landfill Disposal

In north America, a resident generates an annual average amount of 82 pounds of textile waste which 15% gets recycled or donated while 85% (70 pounds) goes into landfill (CBC, 2016; CTR, 2018). Waste diversion from landfill definitely offers savings from landfill cost. An average landfill cost per ton of waste is \$ 46.56 (Eilrich et al., 2002) while the reported average cost to transport a ton of waste to landfill is \$45 which is the main reason of diverting textile waste from landfills (Wicker, 2016). In 2017, almost 11.15 MT of textile waste disposed in landfills (USEPA, 2019a; USEPA, 2019b) and this figure was increasing with year. From the figures mentioned, the estimated landfill cost and transportation cost to landfill can be \$519.14 million and \$501.75

million, respectively. Furthermore, to estimate the volume of landfill space that can be occupied by such quantity of textile waste, the textile waste compaction density is needed for the computation. According to WasteCare Corporation (2013), the compaction density value for mixed textiles are 125-175 pounds/yd^3 (loose) and 600-750 pounds/yd^3 (baled). Considering the loose compaction density to simulate the actual landfill scenario, the volume of landfill space can be occupied is 97.43 million m^3 – 136.4 million m^3.

4.4 Recommendations for Future Studies

The findings of the study recommend to further explore the utilization of local organic waste resources as a component to form biodegradable seedling pots made of textile waste. The hydro-pulping (wet) method used in this study to convert cotton and polycotton waste into its pulp form generates wastewater during the process, hence it is recommended to consider the dry process. The biodegradability (anaerobic degradation and soil burial test) and strength of the formed seedling pots were desirable which make the pots both plantable and compostable at this point whichever the desired purpose of the user. However, it is recommended to perform a plant growth test to investigate the suitability of the pot both as plantable and compostable. Furthermore, an added supplement from organic waste to be incorporated into the seedling pot that can have a slow fertilizer release effect on plant growth could be promising.

Chapter 5: Summary and Conclusions

This study utilized discarded textile waste (cotton and polycotton) and paper waste (newspaper and corrugated cardboard) to make biodegradable seedling pot. A sequential optimization process to enhance the tensile strength of homogeneous sheets and to improve the tensile and bending strengths of bio-composite sheets were performed prior to the development of seedling pots. The homogeneous substrates such as cotton, polycotton, newspaper, and corrugated cardboard were treated using NaOH and $NaHCO_3$ under different concentrations and soaking time. Moreover, the effect of increasing compressive load from 200 N to 500 N on the tensile strength of the sheets was determined. Furthermore, different drying conditions of 103°C-5h, 60°C-72h, 60°C-48h, 60°C-24h, 40°C-48h, and 40°C-24h were investigated. The influence of binding agents such as blackstrap molasses, sodium alginate, and cornstarch at different concentrations of 5%, 10%, 15%, and 20% was also studied.

This study shows that soaking the sheets at 5% NaOH for 5 h obtained an optimum increased in tensile strength by 21%, 19%, and 14% for cotton, newspaper and polycotton, respectively. However, the tensile strength of corrugated cardboard sheets was not enhanced by alkali treatment. Therefore, alkali treatment is an appropriate step for increasing the tensile properties of cotton, polycotton and newspaper substrates, but it is not the same for corrugated cardboard. Moreover, increasing the compressive load from 200 N to 500 N in forming sheets show an improved tensile strength of 14%, 25%, 37% and 42% for corrugated cardboard, polycotton, cotton and newspaper, respectively. Furthermore, an optimum temperature of 103°C for a duration of 5 h for drying the sheets had the highest tensile strength for all substrates. Importantly, the addition of binders show a significant effect on the tensile strength of the sheets, particularly with the use of 20% cornstarch on a dry weight basis per sheet, which increased the tensile strength by 395%, 320%, 310%, and

185% for cotton, polycotton, corrugated cardboard, and newspaper sheets, respectively. An optimum tensile strength of 2.19 MPa, 2.93 MPa, 5.47 MPa and 6.20 MPa with its corresponding specific tensile strength 3.83 MPa/g TS, 5.10 MPa/g TS, 9.82 MPa/g TS and 12.31 MPa/g TS for polycotton, cotton, corrugated cardboard, and newspaper sheets were found, respectively. The higher tensile strength of newspaper and corrugated cardboard imply their potential as substrates to be blended with textiles waste of lower tensile strength.

Moreover, optimized process discussed above were utilized to determine an optimum blend of substrates with improved tensile and bending strength properties. A bio-composite blend of cotton (20% cotton, 40% newspaper, and 40% corrugated cardboard) and polycotton (20% polycotton, 40% newspaper, and 40% corrugated cardboard) attained an optimum strength were formed into seedling pots. The cotton blend pot achieved the optimum tensile strength and compressive strength of 4.81 MPa and 256.64 N, respectively, whereas a comparable tensile strength of 4.14 MPa and compressive strength of 236.13 N were observed from polycotton blend pot. While for the commercial seedling pots, the least tensile strength of 2.49 MPa and compressive strength of 163.60 N were achieved by Jiffy pot and cardboard seed starter pot, respectively. The anaerobic biodegradability assay suggests that the cotton blend pot, polycotton blend pot, and cardboard seed starter pot can be attractively degraded anaerobically because of its biogas and methane generation potential. Cotton blend pot generates an optimum biogas and methane yields 494.30 mL/g VS and 271.80 mL CH_4/g VS, respectively. The % VS degradation after 20 days of anaerobic digestion for cotton blend pot, polycotton blend pot, cardboard seed starter pot, and Jiffy pot were 56%, 51%. 50%, and 32%, respectively. The results correlates with a 120-day soil burial test, the degree of degradation results for cotton blend pot, cardboard seed starter pot, polycotton blend pot, and Jiffy pot were 80%, 78%, 64%, and 16%, respectively. A 100% seed germination results was observed from the four seedling pots tested using lettuce, navy bean, soybean, and mung bean seeds. This implies that the seedling pots has no toxicity effect on the seed growth.

Appendix

List of Abbreviations

Acronym	**Expansion**	**Acronym**	**Expansion**
°C	Degree Celsius	kN	Kilo Newton
ABS	Acrylonitrile butadiene styrene	L	Litre
ASTM	American Society for Testing and Materials	M	Molar
C	Cotton	min	Minute
C blend	Cotton blend	MJ	Mega Joules
CC	Corrugated cardboard	mL	Millilitre
CCME	Canadian Council of Ministries of the Environment	mm	Millimetre
cm	Centimetre	MMT	Million metric tons
COD	Chemical Oxygen Demand	MPa	Mega Pascal
EC	European Council	MSW	Municipal solid waste
EPR	Extended Producer Responsibility	MT	Million tons
EU	European Union	N	Newton
g	Gram	NEWPCC	North End Water Pollution Control Centre
GDP	Gross Domestic Product	NGO	Non-government organization
h	Hour	NMMO	N-methylmorpholine-N-oxide
kg	Kilogram	NP	Newspaper

Acronym	**Expansion**
PA	Polyamid
PC blend	Polycotton blend
PET	Polyethylene terephthalate
PLA	Polylactic acid
RSG	Relative seed germination
SG	Seed germination
SIR	Substrate to inoculum ratio
SRT	Solid retention time
TRC	Textile reinforced concrete
TS	Total solids
US	United States
VS	Volatile solids
W	Watt
w/w	Weight by weight percentage
WTE	Waste to energy
WWTP	Wastewater treatment plant

List of Chemical Formula

Symbol	**Name**
CH_4	Methane
K_2HPO_4	Dipotassium hydrogen phosphate
Na_2CO_3	Sodium carbonate
$NaHCO_3$	Sodium bicarbonate
$NaOH$	Sodium hydroxide
NH_4NO_3	Ammonium nitrate

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