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REVIEW ARTICLE

Chemical recycling of waste clothes: a smarter approach to sustainable development

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Abstract
Amount of fabric waste has increased many folds in the past few years due to increasing population and rapidly changing fashiosn trends. Its larger portion being dumped in the landfills is creating a lot of problem in its management. This is causing problems to environmental components of earth, viz., air, water, and land. Chemically, cotton-based fabrics are made up of mainly cellulose with small components of other chemicals and contribute to a big segment of overall textiles. Along with donating the cloths for various purposes, scientific solutions are also feasible for valorizing waste fabrics to value-added products. This review article focuses on important strategies for addressing fabric waste for their possible conversion to significant products of varied applications. It emphasizes on chemical routes suitable for this purpose for producing cellulose, sugar, composites, etc. This will provide an insight to the readers for understanding the chemical significance of waste fabric and exploring the best possible ways for its efficient management, ensuring a step ahead towards sustainable development.

Keywords Waste cloths/fabrics · Chemical recycling · Waste management · Environmental protection

Introduction

Waste management is growing as the biggest problem of today's world. And it is noteworthy that while talking about large variety of wastes contaminating the planet, such as municipal solid waste, agricultural/horticulture/forest waste, and plastics, a massive segment is missed out to locate, mention, and address the fabric waste. It may be in the form of waste cloth pieces generated out of textile or garment industries or the old cloths which are usually thrown by people due to their non-usage (Picture 1). This may be due to change of fashion or unfit condition of cloths to be used, rapidly changing dressing sense, and trends being the major reasons.1PictureWaste cloths in landfill1PictureWaste cloths in landfill1PictureWaste cloths in landfill

Production of fabrics is increasing rapidly worldwide with increasing population, fastly changing fashion industry, and fabric upgradation. According to an estimate, 56 million tonnes of cloths are purchased and 92 million tonnes of textile wastes are generated yearly across the globe, out of which hardly 15–16% is recycled, and this is expected to be increased to > 93 million tonnes and > 134 million tonnes, respectively, by 2030 (Beall 2020). Average purchase of cloths is ~ 60% more than previous year by a person, creating huge amount of fabric waste in dumping grounds (Greenpeace 2020). Average lifetime of a garment piece is approximately 3 years. In terms of weight, textiles make up to 3% of household waste. Being a larger segment, textile industries producing variety of fabrics contribute a significant role in the economy of nations. Fabric trade across the globe has increased from $ 400 billion in 2002 (6% of world trade) to $ 1.8 trillion in just 10 years (Vaidya 2006; UN_Comtrade 2012). India, China (largest textile producers), and the USA (largest textile importer) occupy distinct places in this context (Huang 2012; Sharma and Dhiman 2016). Textile industry generates two types of wastes: pre-consumer waste (raw material fibers, viz., cellulose fiber, protein fiber, and synthetic fiber, dyeing material, etc.) and post-consumer waste (mainly discarded cloths). Post-consumer waste comprises a mixture of natural/synthetic fibers, zippers (metallic),

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Picture 1 Waste cloths in landfill

buttons (acrylic/wood/shell), and fasteners, which do not allow the fabric to decompose easily (Payne 2015). It occupies a lot of space and may lead to infectious diseases and pollutes the environment in various ways (Ghaly et al. 2014), (Gordon and Hsieh 2006), (Sundar Raj et al. 2009).

Trashing such huge quantity of old cloths in the landfills creates a heavy burden on the environment. Around 5% of landfill is occupied by garment waste globally. Decomposition of natural fibers may take few weeks to years, with a release of CO_2 and CH_4, depending upon the fabric components and landfill environment (Mitchell et al. 2012; The Science Learning Hub 2008). Cotton generally takes > 3 months to decompose, whereas wool takes > 6 months (Li et al. 2010; IWTO(2016)). Fashion industry is responsible for annual contribution of 10% of total green house gas (GHG) emissions, equivalent to 1.2 billion tonnes of GHG to the atmosphere. Additionally, it consumes huge amounts of water for garment production and is responsible for 20% of

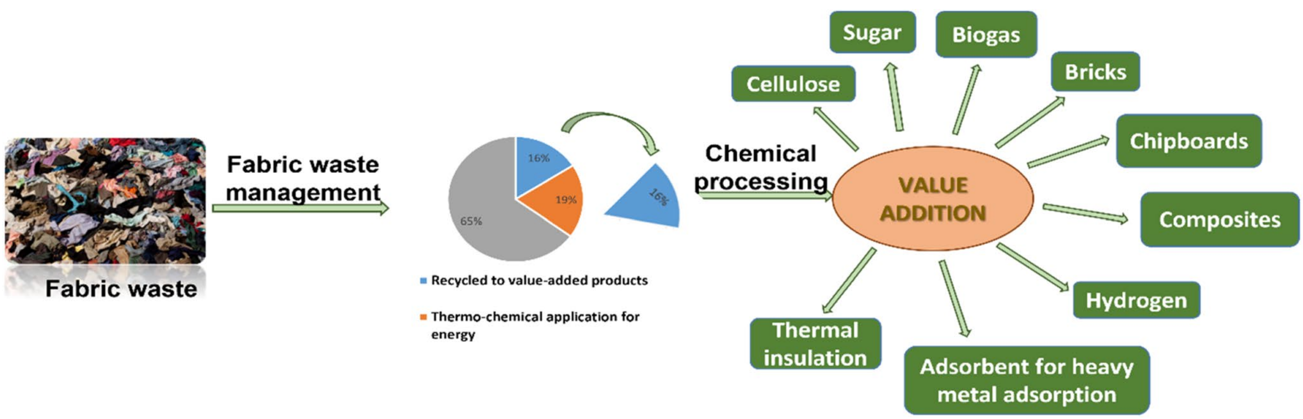

Fig. 1 Overall scenario of fabric waste management

Table 1 Products obtained by recycling fabric waste

S. no	Product	Reference
1	Cellulose	Yue et al. 2012), (Maiti et al. 2013), (Wang et al. 2016), (Scognamiglio et al. 2019), (Yulina et al. 2020), (Xu et al. 2021), (Jiang et al. 2021), (Cavka et al. 2013), (Meyabadi et al. 2014), (Hong et al. 2012), (Singhal et al. 2022)
2	Sugar	Chu et al. 2011), (Shen et al. 2013), (Hong et al. 2012), (Kuo et al. 2010), (Silverstein et al. 2007)
3	Adsorbent for heavy metal adsorption	Bediako et al. 2016), (Nasri-Nasrabadi and Byrne 2020)
4	Biogas	Sundar Raj et al. 2009), (Kabir et al. 2013), (Jeihanipour et al. 2010; Jeihanipour et al. 2013)
5	Ethanol	Jeihanipour et al. 2010), (Mahalakshmi et al. 2011), (Kuo et al. 2014), (Gholamzad et al. 2014), (Jeihanipour and Taherzadeh 2009)
6	Bricks	Algin and Turgut 2008)
7	Chipboards	Binici et al. 2012)
8	Composites	Bakkal et al. 2012), (Bodur et al. 2014), (Dobircau et al. 2009), (Ramamoorthy et al. 2014), (Sun et al. 2014), (Zou et al. 2011)
9	Hydrogen	Chu et al. 2011)
10	In thermal insulation	Briga-Sá et al. 2013)

global waste water (Beall 2020). Release of toxic elements to landfill sites may also destroy ground water and soil in that area. Out of different varieties of fabrics, ~23% is cotton-based material (Preferred Fiber & Materials Market Report 2022). This is a natural fiber derived from plants, but its cultivation, processing, and production also create pressure on environment. For instance, cultivation of cotton needs huge amounts of pesticides and fertilizers (Rana et al. 2014). It is estimated that around 11% of global pesticides are consumed only for cotton cultivation. Its production also consumes a lot of energy with release of CO_2 to the atmosphere. Around 3781 L of water is consumed for producing a pair of jeans (Temmink et al. 2018).

All these factors together have created a pressure on textile and fashion industry to integrate circular economy practices, which significantly depend upon the sustainable practices for managing textile/cloth waste also. Environmental pollution and deceasing value for money due to huge quantity of fabrics being wasted and dumped in the landfill grounds has been the driving force for exploring significant measures for this problem in the form of this manuscript. This review focuses on suggesting feasible value-added solutions for addressing fabric waste in labs, which can be scaled up and utilized as technology at industrial level. This will help in minimizing the amount of waste fabric reaching to the landfill locations along with production of industrially significant products. This may be a radical step in the management of waste cloths, contributing immensely to sustainable growth and circular economy of the nations.

Managing fabric waste scientifically

The concept of three Rs, i.e., reduce, reuse, and recycle as applied to minimize plastic waste, needs to be considered sensibly and seriously for fabric waste as well. Broadly, management of waste fabric is achieved simply by:

- Upcycling the waste cloths by converting them to reusable ones.
- Down-cycling the cloths to other utility items, such as wipers and clutches.
- Reselling these cloths at specified places.
- Donating the cloths to needy ones.

Other than these commonly adopted strategies, systematic measures may also be explored, which can offer scientific solutions to fabric waste by converting it to value-added products. Certain fabrics, like cotton, linen, silk, and hemp, are 100% degradable in nature, which may be subjected to suitable ways for recycling. Synthetic fabrics may even require 20–200 years to decompose (Close the Loop 2020), which indicates its possible processing into composites appropriate for different applications including construction.

Recycling of old cloths and textiles is not conventionally known, however is considered to be environmentally beneficial activity as compared to other options, such as land filling or burning for energy application. In the USA only, the amount of waste textiles generated is > 15 million tons/year, which has doubled over the last 20 years. Noteworthy point is that nearly 100% textile is recyclable, but out of this huge amount, hardly ~16% is recycled, ~19% is combusted to gain energy, and rest ~65% is simply sent to landfill (Environmental Protection Agency 2014). Currently, the common method to recycle older cloths is “material to material” recycling, where an old cloth is converted to new one. Some companies, like “Terracycle” and “Patagonia,” “H&M,” “The North Face,” and “Levi’s,” have established their units for recycling old cloths. Another way of recycling old cloths, especially woollens are their conversion to carpets, but hardly < 1% of woollen cloths are recycled by this method. Reason may be difficult handling of the older cloths being attached with buttons, zips, polyester labels, etc. One significant challenge associated with cloth recycling is its manual sorting, automated systems being in developmental stage.

Chemical recycling

Chemical processing is an effective technique to recycle waste cloths and provides an interesting possibility to convert them to value-added products, which can be used at various places depending upon their forms and properties (Fig. 1). Interest has increased in textile wastes in recent years at global level, as is indicated by the growing number of publications in this area.

Different types of products obtained by processing fabric waste by different routes are summarized in Table 1.

Being a rich source of natural fibers, waste fabric is advantageous while providing a healthier ecosystem in low cost and less energy consumption (Pervaiz and Sain 2003). The biodegradability and recyclability of this waste further intensify its candidature in generating industrially important products. The strategy seems to be sustainable with respect to both economical and environmental aspects. Significant applications of recycling fabric waste are discussed below.

Extraction of cellulose

Cellulose is a natural and renewable fiber present in cotton-based cloths. Chemically, cloth is made up of > 95% α-cellulose (Fig. 2), with few other components in small quantities, such as hemicellulose and trace elements (Sun et al. 2016); however, it generally remains as a mix of its α- and β-anomers.

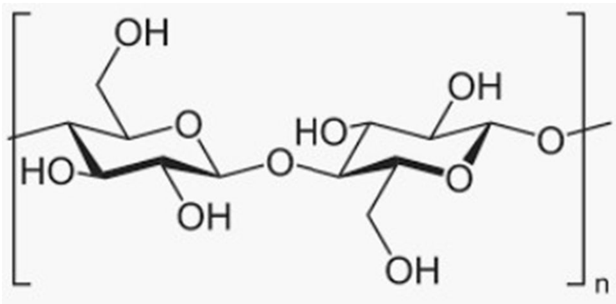

Fig. 2 Structure of α-cellulose

This indicates that waste cloths with higher percentage of cotton in its composition can serve as a promising alternative source for cellulose extraction. Common applications of cellulose are included as fiber supplement in diet, as additive in food items, as anti-clumping agent in cheese, in paper and paperboard production, manufacture of explosives, as stationary phase in chromatography, in cellophane and rayon preparation, in pharmaceuticals and cosmetics, and in industrially significant compounds, like cellulose acetate. For example, Zhong et al. have utilized CNCs isolated from recycled indigo-dyed denim waste under acidic medium as reinforcing agent in polyvinyl alcohol film owing to its appreciable mechanical properties (Zhong et al. 2020). Chuayjuljit et al. applied microcrystalline cellulose (MCC) extracted from waste cotton fabric for rubber filling application. They incorporated various amounts of MCC in latex and observed a remarkable difference in its properties. The modified latex samples showed decreased tensile strength, but enhanced water absorption and biodegradability (Chuayjuljit et al. 2009). The same group extended the studies on the performance of polyvinyl chloride (PVC) films and evaluated that MCC behaved as reinforcing filler to the PVC films (Chuayjuljit et al. 2010). It increased tensile strength and Young's modulus of the blends along with enhanced moisture absorption and biodegradability of the films. Very recently in 2022, cellulose nanocrystals (CNCs) isolated from waste cotton cloths have been used for the biosorption of hexavalent chromium (VI) from aqueous solution at pH 2.0. The study indicates that 1.5 g/L of CNCs could efficiently remove ~ 96.97% Cr(VI) from aqueous solution at 60 °C under strongly acidic medium. The adsorption is reported to be multilayer following second order kinetics (Mohamed et al. 2022). Currently, microcrystalline cellulose (MCC) and nanocellulose (NC) have attracted attention owing to non-toxicity, high crystallinity, high surface area, high modulus, unique optical properties, and biodegradability (Orue et al. 2017). These properties are able to expand the applications of cellulose as reinforcing material, adsorbent, and high-performing films (Lu et al. 2015), (Figueiredo et al. 2015), (Rong et al. 2018). It is, thus, wise to use waste cotton cloths to regenerate cellulose by chemical processing, playing an important role in national economy. It has started seeking attention only around a decade back, and few researchers have explored this aspect of recycling waste cloths successfully. Major steps adopted for cellulose extraction from waste cloths include bleaching and hydrolysis.

Bleaching is done for removing any colored matter from the substrate, and hydrolysis facilitates bond weakening among cellulose molecules in the fabric and making it extractable. Bleaching can be done in the presence of a suitable oxidizing agent. Fenton's reagent, hydrogen peroxide, and potassium permanganate have been used by few researchers for this purpose (Xu et al. 2021; Yulina et al. 2020; Jiang et al. 2021). Hydrolysis of fabric is carried out via chemical/thermal treatment. The size, morphology, shape, and crystallinity of the product varies widely with the reaction conditions, especially the strength of acid used for hydrolysis (Maciel et al. 2019). Sulfuric acid has been used for hydrolyzing waste cloths and converting it to cellulose nanocrystals (CNCs) by Huang et al. (Huang et al. 2020). They adopted a three-stage oxidation process after hydrolyzing the waste textile in acidic medium. CNCs (3–35 nm) with high aspect ratio, good thermal stability, and ~ 55% crystallinity index have been obtained from reused waste cotton cloths in the presence of a dilute solution of mixed acid (H_2SO_4:HCl = 3:1) by Wang et al. (Wang et al. 2017). Studies suggest the prevalence of H_2SO_4 over HCl for hydrolysis owing to the better mechanical and thermal properties of CNCs isolated using H_2SO_4. On the other hand, CNCs are obtained using HCl display low thermal degradation, weak oxidizing ability, and poor dispersion ability (Huang et al. 2020; Fatah et al. 2014). Acid hydrolysis assisted by ultrasonic treatment has been found useful for isolating spherical CNCs from waste cotton cloths (Xiong et al. 2012), (Pandi et al. 2021). Complete scheme for converting waste cotton cloths to CNCs using ultrasonication is depicted in Fig. 3.

Hydrothermal treatment has been adopted for extracting microcrystalline cellulose from waste cotton cloths by Shi et al. (Shi et al. 2018). These studies provide a strong support to the anticipation of chemical recycling of waste cotton cloths for the isolation of cellulose for various purposes. Significant studies carried out by the researchers to chemically process the waste fabric to cellulose in different forms, viz., microfibrills, nanocellulose, and cellulose nanocrystals, are summarized in Table 2.

Enzyme action has also been explored by the researchers for causing the breakdown of waste fabric to cellulose (Meyabadi et al. 2014; Vasconcelos and Cavaco-Paulo 2006). Enzymatic hydrolysis is a cleaner and economic process taking place at milder pH, atmospheric pressure, and moderate temperature (Camacho et al. 1996). However, it is a time-consuming slow process with low

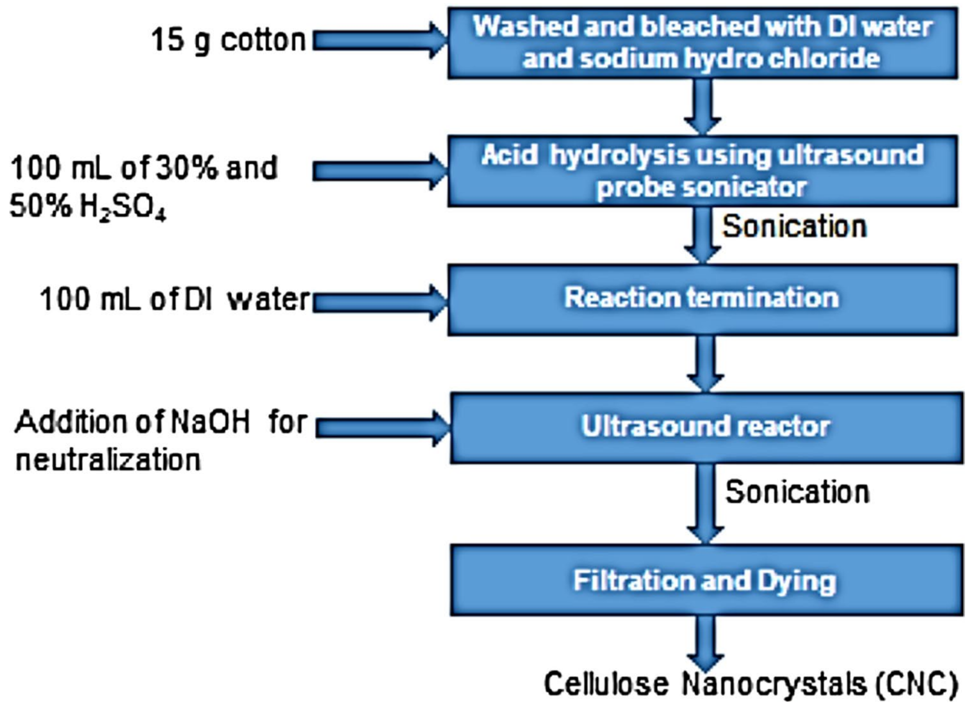

Fig. 3 Step-wise procedure for obtaining CNCs from waste cotton cloths using sonication (Pandi et al. 2021)

yield. This is probably due to the reason that enzymatic hydrolysis of cellulose involves the complex degradation of glucosidic bonds. Ultrasonication helps in loosening the structure of cellulose by the hydrodynamic force and shear stress generated during the process (Wong et al. 2009), (Zhao et al. 2007a). Also, the presence of enzyme causes possible side reactions by converting a significant amount of cellulose to glucose, cellobiose, cellotriose, and cellotetrose, overall decreasing the yield of the process.

This opportunity is taking shape at scaled-up level also at few places across the globe. "Infinited Fiber," a VTT Technical Research Centre of Finland Spin-out, Finland, is producing novel cellulose carbonate fiber from waste cotton. In their process, cotton cellulose is modified by heating it in the presence of urea. It results in its conversion to isocyanic acid, which gives carbamates on reaction with hydroxyl groups of cellulose. This is then converted to pulp, which is used for producing fibers by viscose process. Method is completely environment friendly, and the product is comparable to original cotton. Company is addressing 50 tons of such fiber/annum since 2018 and using it for making T-shirts, sweaters, jeans, and towels [https://infinitedfiber.com/]. The Hong Kong Research Institute of Textiles and Apparel (HKRITA) is working on two novel technologies, funded by H&M, for recycling polycotton. Both of these technologies dissolve cotton component from the blend, leaving polyester fiber behind. HKRITA has introduced "the green machine" using green solvent during the process. Currently, the technique is addressing 100 kg of waste/day and is economically viable. In another process, HKRITA is decomposing the waste under enzymatic conditions in a bioreactor [https://www.hkrita.com/].

Extraction of sugar

Conversion of waste fabric to sugar, routing through cellulose is another good choice for recycling it. Cellulose present in the fabric can be made accessible to chemical (acid, alkali, and ionic liquid), biological, physical, and physico-chemical processes resulting in different levels of structural modifications (Fig. 4).

Hydrolysing agent (acid/alkali/ionic liquids/micro-organisms) plays unique role in a specific way to convert cellulose to sugar by saccharification. Acid pretreatment is most commonly used for hydrolyzing amorphous regions of cellulose smaller saccharides, cellobioses, and some glucose. Sulfuric and phosphoric acid is more commonly used for this purpose, yield of sugar depending upon the reaction conditions including amount of acid used for hydrolysis, reaction temperature, and retention time. Presence of acids hydrolyzes the polymeric molecules into monomers and hence enhances the biodegradability of cellulose. Acid pretreatment offers a simple solution for hydrolysing waste cloths, but poses the disadvantages of formation of side products, reactor corrosion, and low recyclability of acid. These factors increase operational cost and environmental concerns for its safe utilization. Further, stringent operation conditions (high dose of acid, high temperature, and residence time) may lead to the formation of sugar dehydration products also, like furan

Table 2 Important studies for extracting cellulose from waste fabric

Substrate	Method	Outcome	Reference
Waste cotton fabric	Waste fabric → cut and sieve (100 mesh) → cotton fiber + heating with 64% H_2SO_4 (1:10) (45 °C, 60 min.) → dilution to 5 times → centrifugation and decantation → **CNC**	Cellulose nanocrystals (CNC)	Yue et al. 2012)
China cotton	Waste cotton → treatment with H_2SO_4 (60 °C, 120 min.) → centrifugation and washing → neutralization with 0.5N NaOH → washing → freeze drying → **NANO-CELLULOSE POWDER**	Nano-cellulose powder	Maiti et al. 2013)
Waste cotton bedsheet	5 g waste → pulped with 300 ml water (room temp., 10 min) → filtering, washing and drying → boiling with 10% NaOH solution (70 °C, 120 min.) → filtering and washing till pH 10 → addition of 1.5% H_2O_2 and CH_3COOH → filtering, washing and drying → **CELLULOSE** → heating with 98% H_2SO_4, 37% HCl and water (3:1:11) (55 °C, 420 min) → dilution to 5 times → centrifugation → freezing the suspension (− 20 °C, 120 min) → freeze drying (− 60 °C, 1440 min) → **CNC**	Cellulose nanocrystals (CNC)	Wang et al. 2016)
Cotton textile waste	Waste → heating with 96% H_2SO_4 (45 °C, 225 min.) → addition of ice-cold water → decantation for overnight → centrifugation (7000 RPM, 30 min) → neutralization with NaOH → washing till pH 7 → dialysis and sonication → **NCC**	Cellulose nanocrystals (NCC)	Scognamiglio et al. 2019)
Waste cotton from cotton yarn milling mill	10 g cotton lint → treatment with 400 ml of 17.5% NaOH solution (80 °C, 30 min) → washing till pH 7 → treatment with 80 ml H_2O_2 (room temp., 15 min) → filtering and washing → overnight drying → **α-CELLULOSE** → refluxing with 250 ml of 1.25 M H_2SO_4 (80 °C and 96 °C, 120–240 min) → filtering and washing till pH 7 → overnight drying → **MCC**	Microcrystalline cellulose (MCC)	Yulina et al. 2020)
Cotton with short fibers discarded in industrial processes	Discarded cotton (6 g) → heating with solution of 50 ml acetic acid and 60 g sodium chlorite (75 °C, 1 h) → washing till pH 7 → heating with 2% NaOH solution (80 °C, 2 h) → washing till pH 7 → drying under vacuum (55 °C, 12 h) → **COTTON CELLULOSE** → 3 g → treatment with 300 ml Fenton's reagent (30 °C, 1 h) → dilution to reduce the concentration to 25% → treatment with H_2O_2 in sealed tube (110 RPM) → washing till pH 7 → **FENTON-OXIDIZED COTTON CELLULOSE** → high pressure homogenization (60 MPa) → **MFC**	Microfibrillar cotton cellulose (MFC)	Xu et al. 2021)
Waste indigo-dyed denim fabric	10 g denim waste → heating with 10% H_2SO_4 (90 °C, 40 min, bath ratio 1:20) → washing and drying → grinding and sieving (80 mesh) → treating with 0.1 M $KMnO_4$ (60 °C, 30 min, bath ratio 1:50) → washing → treating with 0.1 M oxalic acid (bath ratio 1:20) + 0.2 ml 4 M H_2SO_4/g of oxidized fiber → hydrolysis with 60% H_2SO_4 (45 °C, 30 min, bath ratio 1:8) → addition of ice cold water → washing and drying → **A-CNC**	Cellulose nanocrystals (A-CNC)	Jiang et al. 2021)

derivatives, which are harmful for fermentation processes at higher concentrations (Sun and Cheng 2002), (Wyman et al. 2005).

Alkali pretreatment causes swelling effect and breaks down the chains of cellulose, generating amorphous zones for easing enzymatic hydrolysis (Mosier et al. 2005) by creating porous spaces due to reduced degree of polymerization and crystallinity index. The yield of sugar is relatively higher in alkaline hydrolysis due to improved lignin solubilization and enhanced digestibility of cellulose. Sodium hydroxide, potassium hydroxide, and calcium hydroxide are common alkali deployed for pretreating waste fabric (Jeihanipour and Taherzadeh 2009; Silverstein et al. 2007). NaOH helps in dissolution of cellulose at low temperature, decreasing its crystallinity, making it more available for enzymatic hydrolysis (Cai et al. 2004; Wang 2008). Aqueous solution of urea in alkaline sodium hydroxide also serves this purpose. NaOH functions for destroying inter- and intramolecular hydrogen bonds among cellulose molecules, while urea

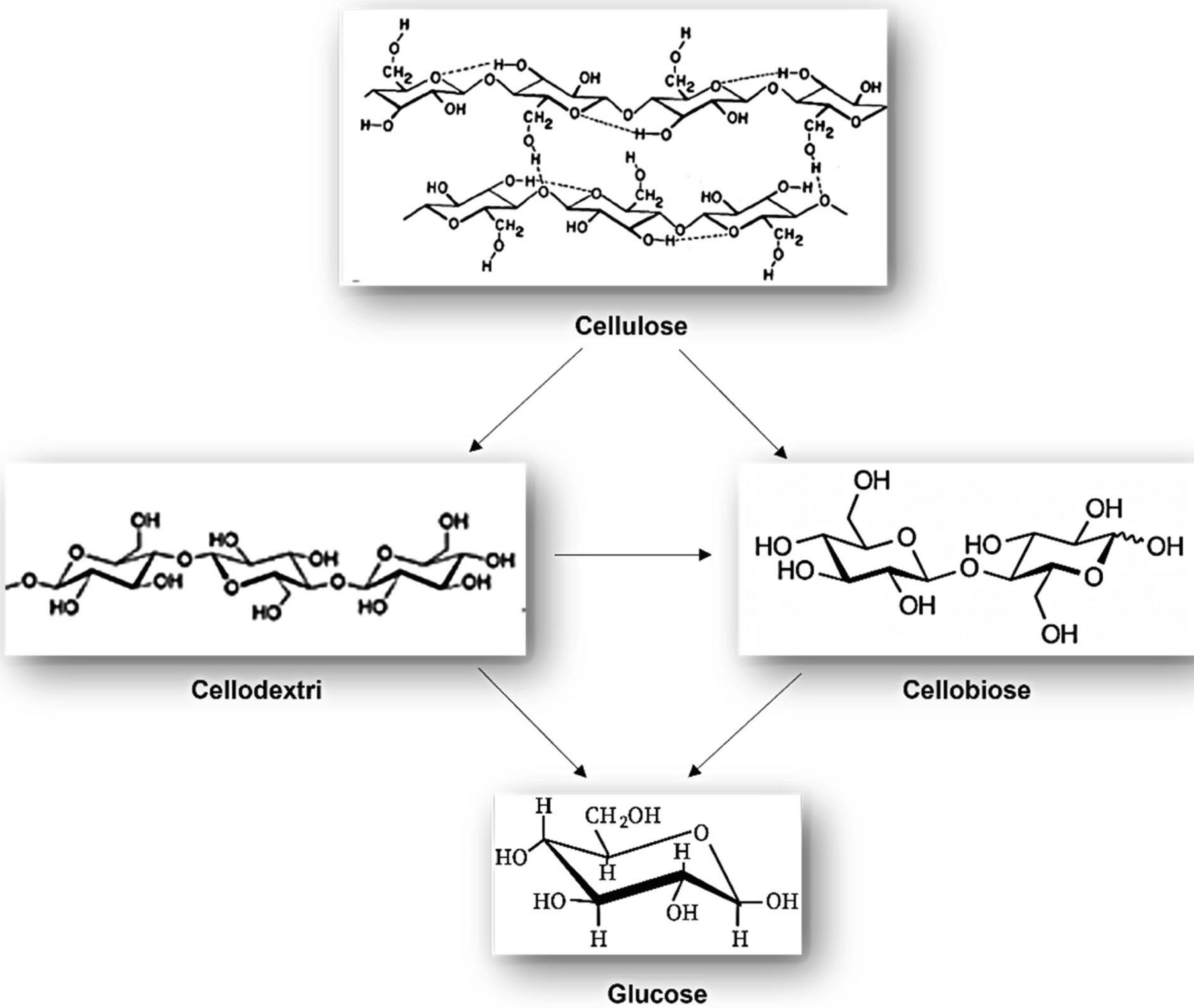

Fig. 4 Chemical/enzymatic conversion of cellulose to sugar adapted from (Kumla et al. 2020)

prevents re-association of cellulose molecules by donating and recepting the hydrogen bond in the solvent (Zhou et al. 2005). Disadvantages associated with alkali pretreatment include long processing time, low concentrations of reaction medium, and requirement for sufficient amount of acid for neutralization.

Ionic liquids are industrially more suitably associated with high chemical/thermal stabilities, liquid form existence, low viscosity, and low vapor pressure (Mäki-Arvela et al. 2010). These alter the structure of cotton waste material during pretreatment by disrupting the non-covalent bonding of cellulose and other components (Tan et al. 2011; Hayes 2009). Few ionic liquids (e.g., 1-butyl-3-methylimidazolium chloride: [BMIM]Cl, 1-ethyl-3-methyl imidazolium diethyl phosphate: EMIMDEP, 1-allyl-3-methylimidazolium chloride: [AMIM]Cl, and N-methyl-morpholine-N-oxide: NMMO) have the capability of dissolving cellulose, which can be regenerated as a more homogenous microfibrillar structure with the help of anti-solvents (water/ethyl alcohol/acetone) (Hong et al. 2012; Guo et al. 2016; Kuo and Lee 2009). Use of ionic liquids is advantageous as these are environment-friendly in nature and can dissolve cellulose at moderate temperatures without causing degradation either of cellulose or the solvent. However, disadvantages associated with ionic liquids include their high production cost, difficult handling, and removal after pretreatment (Zhao et al. 2007).

Enzymatic hydrolysis has also been found successful in generating sugar from the waste (Damayanti et al. 2021a). Enzymes are organic compounds, which act as catalysts for the reaction, remain unaffected by the reaction equilibrium, and are reusable. These are highly specific in nature. For example, commercial cellulase is a mixture of three enzymes, each performing its own function during the catalytic process: (a) *Endoglucanase*, which causes degradation of cellulose chain at different stages, (b) *Exoglucanase*, which degrades cellobiose part of the chain from both the ends, and (c) *β-glucosidase*, which causes depolymerization of cellobiose to monosaccharide units (Duff and Murray 1996). Hydrolysis and degradation of fabric waste in the presence of micro-organisms is advantageous in view of obtaining different products, including sugar, ethyl alcohol, and bioenergy; however, the yield is low in biochemical conversion process. Major outcomes received by the researchers while converting cloth waste to sugar are summarized in Table 3.

A group of researchers at Hong Kong has used fungal treatment for recycling fabrics, made up of cotton and polyester (most commonly used in T-shirts, shirts, and jeans). They used *Apergillus niger*, a black fungus for separating cotton and polyester yarns in the fabric. This fungus produces an enzyme, which decomposes cotton fibers to glucose, which can be used in syrup. The leftover polyester fibers can be used again for preparing cloths. They have scaled up the process by using industrially produced cellulose enzymes and are working with H&M, a clothing retailer to evaluate its recycling impact [https://www.cityu.edu.hk/see/people/dr-carol-lin].

Conversion to bioethanol

Cloth waste can be converted to bioethanol by fermentation; formation is routed via its conversion to sugar only. Cellulose present in the cloth has crystalline structure which is disrupted in the presence of a suitable solvent. The process may vary depending upon the stages involved, like, it can be simultaneous process, where waste is subjected to saccharification, and in situ, it converts simultaneously to bioethanol (Olguin-Maciel et al. 2020; Kuo et al. 2014). Specific microbes, viz., *Zymomonas mobilis*, *Aspergillus niger*, and *Saccharomyces cerevisiae*, are used for this purpose (Damayanti et al. 2021b). Yield of ethanol production is improved in simultaneous saccharification and fermentation by eliminating the end-product inhibition during saccharification (Hasunuma and Kondo 2012); however, more amount of substrate is required in this method. Fast liquefaction and generation of relatively higher amounts of insoluble liquids are major concerns of this technique. Alternatively, the process can be carried out in 2 stages: hydrolysis followed by fermentation under specified conditions (Olguin-Maciel et al. 2020; Dahnum et al. 2015; Leong et al. 2021; Mahalakshmi et al. 2011). The consolidated bioprocessing (CBP) is another strategy, which includes enzyme synthesis, saccharification, and fermentation in a combined process (Okamoto et al. 2014), (Lynd et al. 2005).

Significant studies explored for the conversion of cloth waste to bioethanol are summarized in Table 4.

It may be analyzed from the studies that the methods applicable for the conversion of lignocellulosic wastes to ethanol may not be directly applied to cloth waste due to the difference in the composition and the structure of the two feedstocks. Cloth waste contains polyester fiber also or any other non-cellulose part as blended component, whereas lignocellulosic waste contains hemicellulose and lignin in it in addition to cellulose. Existence of non-cellulosic component and crystalline structure of cellulose creates a need to carry out pretreatment of waste cloth before subjecting it to fermentation, which facilitates its hydrolysis and subsequent reactions impacting the yield of ethanol. Further, it is recommended to bleach the waste cotton cloths prior to hydrolysis as, due to the inhibition of dye molecules in the fabric, rate of reaction may be retarded Gias (Uddin 2016), (Nikolic et al. 2017).

Table 3 Extraction of sugar from waste fabric

Substrate	Pretreatment agent	Reaction conditions	Yield of sugar (%)	Reference
Cotton stalks	Sulfuric acid, sodium hydroxide and hydrogen peroxide, ozone gas, enzyme (cellulase)	50 °C, 72 h	24–61	Silverstein et al. 2007)
Colored cotton T-shirts	N-methyl-morpholine-N-oxide (NMMO), 85% phosphoric acid, enzyme (cellulase AP3)	50 °C	> 90%	Kuo et al. 2010)
Cotton cellulose	55% H_2SO_4	40 °C	64.3–73.9	Chu et al. 2011)
Undyed cotton T-shirts	Ionic liquid, 1-allyl-3-methylimidazolium chloride [AMIM]Cl	110 °C, 90 min	94	Hong et al. 2012)
Waste cotton textile	85% H_3PO_4	50 °C, 7 h	79.2	Shen et al. 2013)
Waste jeans	Phosphoric acid, enzymes (*cellulase* and *cellobiase*)	50 °C, 96 h	67–75	Shen et al. 2013)
Cotton blended with wool and polyester	Enzyme (*Cellic CTec3*® and *Savinase 12 T*®)	50 °C, 70 h	95	Quartinello et al. 2018)
Towels	Enzyme (*cellulase*)	200 °C, 1.8 min	74.2	Sasaki et al. 2020)
Waste jeans	Na_2CO_3, enzyme (*celluclast* and *β-glucosidase*)	45 °C, 72 h	81.7	Hasanzadeh et al. 2018)
End-of-life euro banknote textile	NaOH/urea, enzyme (*cellulase*)	50 °C, 382 h	96	Yousef et al. 2021b)

Preparation of composites

Use of waste fabric as reinforcement material for the production of composites is an interesting area for its recycling. It can serve as a source of the materials containing natural fibers having slight impact on the environment as compared to inorganic fibers. Stringent laws, such as Kyoto protocol, have also been enforced to reduce carbon emission, increasing the need and dependency on natural fibers (Bodur et al. 2014). Advantages offered by natural fibers in context to composite properties include high-specific Young's modulus, high specific strength, low density, and biodegradability (Karmarkar et al. 2007; O-Charoen et al. 2022). Waste cotton-based fabrics can be converted to the composites in the presence of thermosetting or thermoplastic materials using vacuum curing/autoclave/hot-press molding (Lu et al. 2023). These fibers have the advantage of having more entanglement and better interfacial bonding than other fibers for this purpose. Due to this, cotton-based fibers have higher potential to substitute glass in many applications of lesser load requirements. The composites obtained from natural fibers pose slighter impact on the environment due to low cost, high performance, and biodegradable nature (Zeeshan et al. 2021). Mechanical properties while using natural fibers can further be enhanced by applying different chemical and physical methods, such as plasma treatment, alkaline treatment, silane treatment, enzyme treatment, and maleated coupling (Faruk et al. 2012), (Lu john Z, Qinglin W, Negulescu II 2005), (Pracella et al. 2006), (Samal et al. 2009), (Yang et al. 2007). The well-tuned properties make these composites able to replace plastics for different domains including in automobiles and construction.

Few researchers have explored cotton fabric waste for producing reinforced customized composites for several applications and observed remarkable improvement in the properties. The first experimental set-up in this area dates back in 2001 on the recycling of waste carpet fiber by Bateman and Wu (Bateman and Wu 2001). They recycled waste carpet fiber to a novel and environment-friendly polymer-matrix composite and observed the maximum Young's modulus (300 MPa) in the composite matrix containing 50% carpet fiber. Mechanical properties (tensile strength, flexural properties, and failure strain) of the composites are the functions of amount and length of natural fiber in the composite as established by Migneault et al. (Migneault et al. 2008). They suggested a linear relation between the length of natural fiber and mechanical properties of the composites obtained, while the trend was reverse in the experiments of Bateman and Wu (Bateman and Wu 2001). Properties may be enhanced by providing a better layering and adhering technique used for preparing the material. Effect of cotton fibers on epoxy resin composites has been studied by Khan et al. (Khan et al. 2018). The team prepared the composites using oxygen plasma treatment to the mixture. Positive effect of cotton addition was observed on the properties of the composites in terms of surface area and mechanical and tribological behavior. Another study shows the incorporation of 4% addition of fibers to concrete (by weight) as optimum amount affecting the mechanical properties of the composites (Khan et al. 2020). Masood et al. investigated that textile

Table 4 Experimental conditions for conversion of cloth waste to bioethanol

Substrate	Hydrolysis conditions		Fermentation		Yield (%)	Reference
	Pretreatment	Enzymatic hydrolysis (enzyme, temp., reaction time)	Microorganism	Reaction conditions (temp., reaction time)		
Cotton cloth	Na_2CO_3	*Cellulase* and *β-glucosidase* (45 °C, 72 h)	*Saccharomyces cerevisiae*	32 °C, 24 h	69.4	Hasanzadeh et al. 2018)
Waste cotton grinning	H_2SO_4	*Cellic CTec 2 cellulase* (50 °C, 96 h)	*Saccharomyces cerevisiae*	30 °C, -	70	McIntosh et al. 2014)
Cotton + polyester	NaOH/urea	*30 FPU cellulase* and *IU β-glucosidase* (45 °C, 72 h)	*Saccharomyces cerevisiae*	36 °C, 72 h	70	Gholamzad et al. 2014)
Cotton waste	$Na_2S_2O_3$ and Na_2CO_3	*Cellulase AP3* (50 °C, 48 h)	*Zymomonas mobilis*	37 °C, 48 h	90	Kuo et al. 2014)
Cotton + polyester	NMMO	*Cellulase* and *β-glucosidase* (-, 48 h)	*Saccharomyces cerevisiae*	30 °C, 24 h	91.9	Jeihanipour et al. 2010)
Cotton linter + waste jeans	NaOH	*20 FPU cellulase* and *30 IU b-glucosidase* (45 °C, 24–96 h)	*Saccharomyces cerevisiae*	37 °C, 4 days	48	Jeihanipour and Taherzadeh 2009)

waste (after mercerization and desizing) is a good reinforcing agent to the virgin material for maintaining the mechanical properties with reduction in cost (Masood et al. 2018).

Few significant studies are summarized in Table 5.

Sadrolodabaee et al. (Sadrolodabaee et al. 2021) prepared composites from non-woven fabric for construction application. The recycled short fibers were investigated for their mechanical and durability properties. The composites showed improved toughness and post-cracking control capacity as internal reinforcement for enhancing ductility and cracking control. Consumption of fabric waste fibers for building applications has also been investigated by Echeverria et al. (Echeverria et al. 2019a). They prepared the composites from the assorted textiles comprising of cotton, wool, polyester, nylon, acrylic, polypropylene (PP), and elastane fibers with PP textile as the matrix. Composites prepared with 40% matrix (by weight) displayed maximum mechanical strength of 34.9 MPa and the moisture absorption was as low as 2.4%. The compositions were found more suitable for load-bearing applications as compared to the standard wood-based particle boards. Arif et al. (Arif et al. 2022) developed composite materials from post-consumer and post-industrial denim waste using polyethylene and polycarbonates as thermoplastic matrices. They observed that polycarbonates serve as better material as matrix resulting in the composites with tensile strength and flexural strength ranging between ~ 26 and ~ 38 MPa and ~ 910 and ~ 1350 MPa, respectively. They proposed the applications of the composites in floor tiles, automotive interiors, packaging material, door panels, etc. Other researchers have also used textile fabrics for preparing composites, particularly for construction and building application (Ventura et al. 2022), (Lahtela et al. 2021), (Sadrolodabaee et al. 2021).

Various research groups are working for converting fabric waste to composites and exploring their novel findings for useful applications (Surtiyeni et al. 2016; Todor et al. 2021; Temmink et al. 2018; Song et al. 2021). Patti et al. (Patti et al. 2021) have summarized different applications of the composites derived from waste fabric in their recent review in a very concise manner (Table 6).

Bricks manufacturing

Utilization of cotton fabrics into bricks is a potential way to convert waste into wealth. Teklehaimanot et al. (Teklehaimanot et al. 2021) used cotton microwastes from textile industries in different ratio with sand and cement to form lightweight brick for construction sector. The bricks satisfied the standard test for construction bricks like compressive strength, unit weight, and water absorption properties. Forty percent of cotton waste was found to be the optimum amount to be mixed with soil. On further increasing the percentage of cotton waste, compressive strength and water absorption property increased but the mass of the brick decreased. Wang et al. (Wang et al. 2021) prepared fabric reinforced cementitious material and used it for seismic resistant buildings. A company, FabBrick, has set up machines to prepare ecological, thermal, and acoustic insulator bricks using discarded cloths. A 400-g eco-friendly brick required around three discarded T-shirts (Fab.Brick 2021).

Conversion to adsorbent

Another promising approach to the value-added management of cellulose-based fabric waste is its thermal conversion to carbon-based adsorbent, i.e., biochar. This is an important material, gaining interest nowadays for various applications, such as water treatment for the removal of dyes and heavy metals, deodorizing agent, and construction industry (Singhal 2022). Yousef et al. (Yousef et al. 2021b) pyrolyzed cloth waste to prepare synthetic product (graphene oxide–carbon nanoball and carbon nanotube-carbon nanoball) by chemical treatment and applied the compositions for improving cement characteristics. Xu et al. in 2020 prepared char-$FeCl_3$, char-$FeCl_2$, and char-FeCit (char-based adsorbents) from cotton textile waste and found excellent results for the removal of Cr(VI) from the solution. Among the three, the best adsorption capacity was found to be for char-$FeCl_3$ (73.79 mg/g), followed by char-$FeCl_2$ (68.87 mg/g) and char-FeCit (43.84 mg/g) (Xu et al. 2020). Removal of other ions, such as fluoride ion, cadmium, copper, and lead, has also been achieved using different types of cotton-based adsorbents after appropriate modifications (Mendoza-Castillo et al. 2016; Ma et al. 2018). Wanassi et al. (Wanassi et al. 2017) used cotton waste derived char for the removal of Alizarin Red S and found its maximum adsorption capacity to be 74 mg/g at 25 °C and pH 3. Silva et al. (Silva et al. 2018) used the biochar obtained by pyrolyzing phosphoric acid modified denim waste for the removal of Remazol Brilliant Blue R dye. Akkouche et al. (Akkouche et al. 2020) used fabric-based adsorbents for the removal of pharmaceutical drugs from wastewater. Char made from cotton textile waste was activated by different concentration of H_3PO_4 and then found to be effective for the adsorption of tetracycline and paracetamol. Adsorbent developed using 1 M concentration of H_3PO_4 was found to be most effective with maximum adsorption capacity of 87.7 mg/g and 62 mg/g for tetracycline and paracetamol, respectively, at pH 3.8. Other than heavy metal ions, dyes, and pharmaceutical drugs, modified textile adsorbents have been found effective in the adsorption of oils and organic solvents also. In a study, carbonized material was made from carbon fibers produced from waste cotton textile. Prior to carbonization, carbon fibers were modified through freeze drying and CO_2 activation in order to increase

Table 5 Extraction of composites from waste fabric

Substrate	Composition	Die temp. (°C)	Density (g/cm^3)	Tensile strength (90°) (MPa)	Melting point (T_m) (°C)	Impact strength (KJ/m^2)	Crystallization point (T_c) (°C)	ΔH (J/g)	Crystallinity %	Young's modulus (MPa)	Reference
Waste cotton fabric	LDPE + cotton fabric (12.5%)	180	-	6.50	114.86	194	96.31	107.03	41.74	-	Bakkal et al. 2012
Waste cotton fabric	LDPE + cotton fabric (25%)	180	0.946 ± 0.005	6.55	114.56	122	-	-	-	-	Bakkal et al. 2012
Waste cotton fabric	LDPE + cotton fabric (15%)	165–180	-	35.6	-	-	-	-	-	1612	Bodur et al. 2014
Waste plain-weave bed linen	Plasticizers + matrix + waste fabric (40%)	130–150	-	62–88	-	24–38	-	-	-	-	Ramamoorthy et al. 2014)
Waste cotton fabric	PVA + waste fabric (5–15%)	80	-	~35–46.5	215–219	-	-	45–68.7	35–44.9	200–800	Sun et al. 2014)
Waste cotton fabric	PET + waste fabric (35%)	35	-	21.4–34.3	-	-	-	-	-	2400–3200	Zou et al. 2011)

the surface area and porosity. Maximum adsorption of this carbonized material was reported in the range of 75–175 g/g for various substances like ethanol, heptane, chloroform, gasoline, and olive oil (Nasri-Nasrabadi and Byrne 2020). Results have been summarized in Table 7. Adsorbents developed from textile waste also find applications as deodorants as well. In order to establish the fact, Cay et al. (2020) prepared biochar from cotton, cotton/polyester blend (1:1 blend ratio) and acrylic fibers and applied it on another fabric through conventional printing method. The adsorbent (material) was found to be effective for its deodorizing properties for isovaleric acid, the major reason of strong foot odor. Cotton-based biochar has found application as active electrode battery material too. Jagdale et al. (Jagdale et al. 2021) used pyrolyzed cotton waste and used the carbon as active electrode battery material. The material demonstrated outstanding cycling behavior and provided a high discharge capacity, with a voltage range of 0.02–1.2 V. Electrochemical efficiency of cloth-waste-derived biochar has been validated earlier also (Adinaveen et al. 2016). Catalytic pyrolysis of cloth waste has also been applied by few researchers for obtaining a range of aromatic compounds, such as toluene, benzaldehyde, phenol, acetophenone, and furan derivatives (Yousef et al. 2020), (Silva et al. 2021).

Instead of converting to char, cotton waste can also be directly used as adsorbents after chemical treatment. In this direction, recently in 2021, studies have been carried out on waste cotton textiles from the cutting of knitted fabric and H_3PO_4-treated cotton waste. Adsorbents were used for effective removal of the dye, Reactive Red 84 (RR84). Studies revealed that waste cotton textiles from the cutting of knitted fabric showed pseudo-first-order while chemically treated adsorbent showed pseudo-second-order kinetics (Micic et al. 2021). In another study, household textile waste was grafted by polyacrylic acid using copolymerization process and then chelated by ethylenediamine solution. Chelated fibers were used for the removal of Pb(II) and Cr(VI) ion from solution. The maximum adsorption capacity was found to be 2.17 and 1.85 mg/g for Pb(II) and Cr(VI) respectively (Racho and Waiwong 2020).

Generation of biogas

Being rich in cellulose content cloth waste is suitable for its conversion to an important source of renewable energy, i.e., biogas, which comprises mainly methane in its composition. Few researchers have experimented on finding the possibility of anaerobic digestion (AD) of cloth waste in the presence of required micro-organisms to convert it to biogas. Sundar Raj et al. (Sundar Raj et al. 2009) investigated the biochemical methane potential (BMP) of cotton waste from cotton spinning mills in batch type reactor as 40 L biogas/

Table 6 Application areas explored for fabric-waste derived composites

Application	Fabric source	Matrix	Reference
Light-weighted and medium load applications	Jute	Epoxy resin	Dinesh et al. 2019)
Structural reinforced components and green packaging	Cotton	Poly(lactic acid)/thermoplastic starch	Macedo et al. 2019)
Reduction of noise pollution	Waste of knitted cotton	Polyurethane foam	Tiuc et al. 2016)
Structural applications	Knitting waste	Unsaturated polyester resin	Umar et al. 2017)
Particle boards, plywood, and flooring	Waste jeans	Epoxy resin	Meng et al. 2020)
Automotives and buildings	Industrial cotton waste	Epoxy resin	Baccouch et al. 2020)
Substitute of wood for furniture and automotive components	Garment cutting waste	Epoxy resin	Kamble and Behera 2020)
Automotive components	Waste carpets	Recycled polyamides	Kiziltas et al., 2012
Automotive components	Denim waste	Polypropylene	Araújo et al. 2017)
Insulating panels	Recycled jeans	Sodium alginate	Lacoste et al. 2018)
Thermal and acoustic insulation	Industrial cloth waste	Gum Arabic and Chitosan	Rubino et al. 2019)
Non-flammable and insulating building materials	Recycled jeans	Chitosan	Hage et al. 2019)
Flexible strain sensor	Waste cardigans	Natural rubber latex	Chen et al. 2019)
Sound insulation	Knitted cotton and polyester	Natural rubber	Dissanayake et al. 2021)
Floor tiles, automotive interiors, packaging material, door panels, etc	Waste denim	Polyethylene and polycarbonates	Arif et al., 2020
Sound absorbing materials	Waste cloths	Recycled polypropylene	Echeverria et al. 2019b)
Buildings and construction	Industrial waste cloths	PLA/PBAT blend (55/45% wt.)	Muthuraj et al. 2019)
Furniture and automotive components	Textile waste	Epoxy resin	Kamble et al. 2022)
Protection of sea environment	Waste fishing nets	Cementitious mortar	Spadea et al. 2015)
Corrosion-resistant concrete	Waste carpets	Portland cement	Mohammadhosseini et al. 2018)
Interior partition	Waste jute bags	Portland cement and starch	Ferrandez-García et al. 2020)

kg of cotton waste under mesophilic-thermophilic conditions. The hydraulic retention time (HRT) of the process was 50 days. The study can provide an advantageous opportunity to the spinning mills to use their non-profitable cotton waste for the regular in-house production of biogas. Textile waste mixed with cellulose regenerated from textile waste was digested anaerobically by Jeihanipour et al. (Jeihanipour et al. 2010) under thermophilic conditions (55 °C) in the presence of inoculum. They suggested that (1) viscose-types fibers are more prone towards AD as compared to cotton fibers and (2) pretreatment of the fibers with suitable solvent, such as NMMO enhances the rate of AD resulting in the increased yield of biogas. This is due to the fact that solvent facilitates the dissolution of cellulose followed by its precipitation. It makes its degradation easier in the presence of enzymes by causing structural changes. Jeihanipour

Table 7 Removal of various components by utilizing modified textile cotton waste

Waste	Material	Surface area (m^2/g)	Max. adsorption capacity (mg/g)	Component removed	Reference
Textile cotton waste	Char	292	74	Alizarin Red S	Wanassi et al. 2017)
Textile cotton waste	Char-$FeCl_3$	78	73.79	Cr (VI)	Xu et al. 2020)
Textile cotton waste	Char-$FeCl_2$	43	68.87	Cr (VI)	Xu et al. 2020)
Textile cotton waste	Char-FeCit	13	43.84	Cr (VI)	Xu et al. 2020)
Textile cotton waste	CO_2 activated freeze-dried carbon fibers	312	75–175 (g/g)	Ethanol, heptane, chloroform, gasoline, olive oil	Nasri-Nasrabadi and Byrne 2020)
Textile cotton waste	H_3PO_4 (1 M)	416	87.7 (tetracycline), 62 (paracetamol)	Tetracycline, paracetamol	Akkouche et al. 2020)

et al. (Jeihanipour et al. 2013) utilized NMMO in another study also for digesting waste jeans fabric anaerobically and converting it to biogas via a two-stage continuous stirred tank reactor (CSTR).

Waste wool has been digested anaerobically by Kabir et al. (Kabir et al. 2013) after appropriate pretreatment of the fibers under three different conditions: thermal pretretament, enzymatic pretreatment in the presence of alkaline endopeptidase (Savinase® 16 L), and thermal followed by enzymatic pretreatment. They subjected pretreated wool fibers to AD under thermophilic conditions for 46 days and obtained maximum methane yield (0.43 Nm^3/kg VS). Combined pretreatment (thermal followed by enzymatic) strategy was found to be most effective among the three. Wool mainly comprises protein (keratin), which causes hindrance in its AD due to the presence of disulfide bridges and other intermolecular interactions (Feughelman 1997). Pretreatment initiates the breaking of these linkages, exposing the digestion-susceptible sites, which promotes the enhanced yield of methane.

Other researches have also explored the possibility of converting waste textiles to biogas (Guha and Said 2016; (Rasel et al. 2019). Studies report the successful conversion of waste cloths to biogas, which may be a feasible choice for bioenergy generation to an extent. Looking at the other side of this, there seem certain challenges or incompleteness in this application. For example, the design of the reactor for digesting waste cloths needs to be completely a different model from the conventionally used reactors. Even after pretreatment, it is very difficult to completely decompose the waste cloths in the suggested reaction time; this will lead to the problem of sludge settling at the bottom of the reactor in very less time, which otherwise is drained out in the decomposed form along with the outcoming slurry. This may require an additional effort to clean the reactor frequently, creating the need of a modified design for anaerobic digestion of waste cloths. Further, researchers have not discussed about the quality and possible ways of management of the slurry coming out after the experiment. These two main concerns need to be thought wisely to make this route of managing waste cloths economically viable and sustainable.

Thermal and acoustic insulation

Utilizing the waste cloths for thermal and acoustic insulation is relatively a unique but widely explored application in construction domain. Filling the air-box with cloth waste between the layers of masonry walls is an effective strategy to provide thermal and acoustic insulation to the structure. The porosity in the structure of material helps in dissipation of sound within the pores. Waste cloths being rich in porous structure offer potential ability for this application. Briga-Sá et al. (Briga-Sá et al. 2013) investigated the potential of woven fabric waste in external double wall and observed 56% increase in its thermal behavior. The performance was comparable to expanded polystyrene, extruded polystyrene, and mineral wool. Patnaik et al. (Patnaik et al. 2015) prepared different thermal and sound insulation samples for building applications from waste wool and recycled polyester fibers. The mats prepared from polyester fibers and waste wool (1:1) were able to absorb > 70% incident noise in the frequency range 50–5700 Hz. This combination also displayed adequate moisture resistance under highly humid conditions without affecting insulation or acoustic properties. The mat was analyzed to be biodegradable in nature (65–70%) over a period of 50 days. Similar thermal properties have been evaluated by Sakthivel et al. (Sakthivel et al. 2020) while studying a blend of recycled cotton fiber and PET fiber in 50:50 ratio in the form of two-layer non-woven mats. Thermal conductivity in the range of 0.03745–0.04581 W/m K has been observed in thermal insulation material prepared by textile waste by Gounni et al. (Gounni et al. 2019). Fiber length of the waste, percentage of waste, volume density, hot processing temperature, thickness of material, and the rear layer are the important parameters affecting the sound absorption properties of the structure. Fibers with high density enhance sound absorption ability in mid to high frequency ranges (Koizumi et al. 2002). Nonwoven structures have appreciable sound absorption in mid and high frequency ranges, while low sound absorption in lower frequency ranges (Seddeq et al. 2013). On the other hand, thermal insulation is governed by the porosity of the material and the ratio of its open pores to thickness (Smith et al. 2013; Hadded et al. 2016). Among variety of cloth waste, cotton, synthetic, wool fibers, jute, nylon, and polyester are potential sources for thermal and acoustic applications (Trajković et al. 2017; Drochytka et al. 2017; Berardi and Iannace 2017). Different types of processes and effect of different types of textile fibers on thermal and acoustic insulation of structures have been elaborated in detail by Islam and Bhat in their review article published in the *Journal of Environmental Management* in 2019 (Islam and Bhat 2019). Waste wool fibers blended with polyamide fibers have been evaluated for sound absorption and flame retardant property by Lyu et al. (Lyu et al. 2020). They prepared the non-woven wall cloth by combining the two fibers by hot pressing method (110 °C) and tested them for the targeted properties. The sample prepared by incorporating 50% waste wool fibers displayed the maximum sound absorption coefficient above 0.91. Study carried out by Wazna et al. (EL wazna et al. 2020) suggests that insulators prepared from cloth waste have higher heat reduction capability with an average reduction of approximately 49% as compared to the standard materials. Synthetic fibers are also helpful in enhancing the acoustic properties of polyurethane foam, a commercially used material for different applications both in indoor and outdoor environment (Tiuc et al. 2016). Despite different fibers being explored for this purpose, the compositions with higher cotton fiber content show better thermal insulation property (Sedlmajer et al. 2015).

Other applications

Few other application areas for managing fabric waste may be as follows.

Composting

Waste cloths made up of cotton, linen, silk, and wool can be broken down to smaller segments and composted. Removal of non-biodegradable material in the cloths, like zips and buttons, needs to be done before subjecting it for composting. It offers all the benefits as are offered by composting horticulture, vegetable, and other wastes:

- It improves the structure of soil by providing important nutrients to it, balancing pH level, and permitting adequate moisture. Microbes present in compost soil make it aerated and fertile.
- It helps in revitalizing and filtering local water resources.
- It cleans oceans by decreasing water run-off to ocean bringing chemicals with it.
- It helps in controlling erosion caused by excess water. Compost bed acts like a sponge and provides passage to additional amount of water to ground, maintaining the top layer of soil in its required and original position.
- It reduces GHG's emission to the environment by not letting the biodegradable material to decompose in open.
- It helps in CO_2 sequestration from the atmosphere.
- It can minimize dumping yard area.

Fabric composting can be done simply by shredding after removing the non-decomposable material (buttons, zips, synthetic tags, rubber prints, etc.) and mixing it with compostable organic matter (with no more than 25% fabric in it). Fabric addition needs to be kept at the centre of the pile, where temperature is maximum. On completion of composting process, fabric disappears from the pile and can be tested for nutrient value (Fletcher 2020).

Despite the known benefits, very less research has been carried out on composting waste fabric. Limited studies have been carried out on only some fabric types (linen, cotton, silk, and muslin) by few research groups and have successfully used it for better plant growth. Aishwariya and Amsamani (Aishwariya and Amsamani 2012) evaluated the efficacy of textile waste for converting it to biofertilizer. They treated the waste by a three-tier system creating enzyme-earthworm-microbes interaction to generate vermicompost with appreciable amount of nitrogen, phosphorus, and potassium content (NPK) in it. Composting fabrics is feasible but complicated process due to the involvement of variety of chemical structures and materials involved in it. The interwoven structure of fabrics causes delayed decomposition (sometimes up to ~ 1 year) as compared to vegetable/fruit peels (Jackson 2020). Additionally, non-crosslinked fabrics show better decomposition than crosslinked fabrics (Smith et al. 2021). Li et al. (Li et al. 2010) used three sets of treated cotton jersey fabrics (scoured and bleached, softener added, and resin added) and a polyester jersey fabric for composting in controlled environment for 3 months. All cotton fabrics degraded significantly,however, among all, cotton fabric with softener showed enhanced decomposition in comparison to bleached and resin-treated cotton fabrics. On the other hand, polyester fabric did not show much degradation under the given environment. In another study, cotton waste was successfully vermi-composted at 40–50 °C. Waste fabric acted as a carbon source to the worms and produced mature compost to be used as fertilizer (Singh et al. 2022).

Thermo-chemical application

Thermo-chemical methods for managing fabric waste include incineration and briquetting. Incineration of waste cloths to gain energy is commonly used owing to the high-energy content present in it. A blend of cotton and polyester produces 16 MJ/kg of heat at 700 °C (Ryu et al. 2007). The process, however, is associated with the release of dioxins, which have adverse effect on the lives and environment in the long run. This group of chemicals affects the normal functioning of hormones, damages immune system, and is also carcinogenic in nature (WHO(2016)). Incineration may remove around 96% of fabric waste, but the extent by which it damages the environment is not acceptable.

Briquetting is another option for utilizing fabric waste after its drying and compacting. Gross calorific value (GCV) and net calorific value (NCV) for briquettes prepared from textile waste are 27.79 and 26.37 MJ/kg, respectively, which are comparable to GCV (31.18 MJ/kg) and NCV (29.97 MJ/kg) of briquettes prepared from coal (Campbell et al. 2000).

Paper manufacturing

Paper manufacturing is another suitable perspective for utilizing waste fabric. This can be helpful in producing paper for various applications, such as tea bags, carry bags, and envelopes, and even high-quality handmade paper (Aishwariya 2018). This provides an opportunity to reduce pressure for deforestation, reducing carbon emissions.

Challenges of cloth recycling

Rapidly increasing amounts of fabric waste demand appropriate methods for its efficient management, reducing pressure on environment. Opportunities and technologies propose promising routes (not limited to) for valorizing fabric waste efficiently, offering advantages like reduction in landfill area requirement, protection of environment, and a strong support to circular economy. Despite the remarkable developments in terms of optimization and expansion in the efficacy of these methods, certain challenges are also evident with the overall strategy at various stages:

- Collection and segregation of fabric wastes is a big challenge faced during its processing. Due to the non-availability of commercially viable solutions for waste segregation, this step becomes highly expensive requiring loads of human efforts and time. A study indicates that the Trans-America Trading Company (USA) is active in textile waste management and processing. The company addresses around 12 million pounds of textile waste/annum and spends a lot of human efforts, time, and money for segregating > 300 types of textile wastes (Luz 2007).
- Innovated fabrics in modern times are the blends of cellulose with certain synthetic materials, which require special attention to be processed carefully in affordable cost. The differences in their structure-property relationships affect the selective separation of the required component quantitatively and qualitatively (Haslinger et al. 2019). For example, in our own work (Singhal et al. 2022), the characteristics of the microcrystalline cellulose (MCC) extracted from the waste cloths were slightly different from the commercial sample of MCC; however, the results were in complete alignment with the studies reported earlier on the similar precursor (Xu et al. 2021; Jiang et al. 2021; Meyabadi et al. 2014; Hou et al. 2019). Similar observations have been made by Haslinger et al. (Haslinger et al. 2019) while separating cellulose and PET fibers from a cotton-polyester blend-based textile. This may be due to the presence of impurities and the interlinkages of two or more varieties of fibers woven in the fabric, which makes it difficult to break in its natural state.
- All the recycling techniques cannot be applied uniformly to all the varieties of waste cloths. The recycling method is specific with the type of fiber present in the waste. For example, cotton-based fabric can be used for the extraction of cellulose, while synthetic fibers are better for composite preparation. Thus, a wise thought and well-planned strategy is required for managing different types of cloth wastes.
- A sustainable revenue model inclusive of an adequate cost-effective recycling process with maximum efficiency is challenging. To achieve sustainability, technology should also be environment-friendly in nature. Various studies are reported in this domain proposing different recycling options for waste cloths; these include the use of high concentrations of chemicals and require intense energy to complete the process. Thus, it is really challenging to explore the possibility of reducing this requirement and making the process a sustainable and environmentally friendly in nature.
- Life cycle assessment (LCA) of a course of action is crucial to understand the potential environmental impacts throughout the entire process. This covers all the stages beginning from its generation till its final disposal, even by incineration. Life cycle impact assessment needs to abide with the guidelines of The International Organization for Standardization. LCA carried out by Subramanian et al. (Subramanian et al. 2021) reveals that the valorization of cotton cloth blended with polyester is environmentally favorable if the use of chemicals and reaction parameters applied for hydrolysis facilitates the enzymatic access to the internal structure of cellulose and optimizes energy consumption.
- Financial investment to set-up the unit at large scale is another challenge calculated as a part of circular economy for textile industries. The cost of waste collection/procurement, operational cost, regeneration, and electricity consumption are important for overall economics of the process.
- Public awareness and sensitization towards the recycled products are less receptive. This leads to a suppressed market for recycled material, overall reducing the consideration of investors also towards the possibility of recycling this waste.

Future recommendations

Chemical recycling is potential solution for managing cloth waste. Different possibilities have been elaborated in this paper with an intention to make the scientific community aware of the opportunities for addressing fabric waste scientifically. Effective valorization of waste cloths to produce useful products of daily life applications would present a remarkable milestone in establishing the role of cloth waste management in the circular economy. This may be a guiding tool for better management of the waste to the best possible extent (if not all) and converting it to useful products. Despite notable research going on in the labs at individual levels, certain attention areas are crucial to make cloth waste management sustainable in the current context, which can be referred as the indicatives for the researchers working in this area.

• Region-wise quantification of cloth waste will be helpful in generating a baseline data set for understanding the unit-size for recycling. A better picture may be created by further segregating the waste on the basis of the fiber present in it. This data set will be helpful in estimating the product quantity and its potential market.
• An efficient system for collecting and segregating textile/cloths wastes is essential for recycling the waste. This also includes transportation of the waste to the recycling sites.
• Chemical recycling/valorization process of waste involves different types of chemicals in inflow as well as in outflow routes. Thus, the process is not completely environmentally benign, which needs concern for its sustainable existence for the purpose. Few green methods need to be explored to make the process efficient without creating any adverse impact on environment.
• Currently, the research attempts in this direction are restricted to laboratories only. Efforts need to be scaled-up in order to transform them to sustainable technologies, which can contribute to the technological and economic growth of the region.
• Public awareness and participation is important for achieving any objective. Awareness campaigns ought to be organized for people targeting on the importance of disposing-off the waste wisely. They need to be taught for keeping their cloth waste separate and hand it over to the recycling units to their nearest locations. This will minimize the efforts required for collection, segregation, and transportation strategy framework.
• Favorable policies (guidelines, standards, specified funding schemes, pilot projects, incentives, etc.) with the support of local government and policy-makers are vital to provide a strategic shape and holistic approach to this concept.

A synergistic framework comprising the partnership of all the stakeholders will be an appropriate approach for getting rid of discarded cloths and converting them to value, which can be a real contributor to the development and the circular economy of a country.

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Shilpi Agarwal: reviewed the manuscript and supported in references.
Naveen Singhal: reviewed and formatted the manuscript.

Data availability The data given in review paper is available in the research papers for which references have already been given.

Declarations

Consent to participate NA.

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