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ChemBioEng Reviews

Anaerobic Digestion for Textile Waste Treatment and Valorization

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Abstract

Textile waste is becoming among the most polluting waste in the world, discarded mostly in landfills. Valorizing textile waste via anaerobic digestion (AD) helps conserve resources, reduce environmental impact, and foster a circular economy. Although several reviews have discussed textile waste AD, there is a lack of detailed understanding of the challenges encountered during textile waste AD. Therefore, the goal of this review is to focus on challenges encountered and possible solutions for those challenges for biogas and fertilizer conversion via AD. Potential strategies include chemical, biological, and thermal pretreatments that significantly increase the digestion process. Co-digestion of natural textile waste, cotton, and wool with carbon and nitrogen-rich substrates improves AD efficiency by twofold. Moreover, separating polyester from polycotton and textile dye removal via solvent and advanced oxidation processes significantly increases methane yield compared with untreated textile waste. This review can aid in analyzing suitable methods to optimize the biogas production of textile waste via AD.

Keywords: Anaerobic digestion, Biogas, Fertilizer, Natural fiber, Textile waste, Waste valorization

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1 Introduction

Population growth significantly increases the amount of textile waste, a factor of fast fashion that contributes to one of the most polluting sources in the world [1, 2]. Fast fashion causes a global issue as fast fashion producers produce many new clothes every week, encouraging overconsumption. Cheap clothing continuously stimulated the market and is referred to as fast fashion. Millions of tonnes of discarded clothes are produced globally as a result of the overconsumption of garments [3]. As the production of textiles impacts the environment, campaigns and the government should impose stringent regulations on textile waste management to educate the public about the adverse effects of disposing of textile waste.

Available statistics show that the global average production of textile waste amounts to 92 million tonnes annually [4]. In 2022, China and the United States will be the two biggest textile waste producers, producing 20 and 17 million tonnes, respectively [4]. The fraction of textile waste disposed of annually that is most significant is 65 % synthetic fibers (mainly polyester), 21 % cotton, 8 % cellulosic fibers, 1 % wool, and 5 % other [5]. This waste may contribute to severe problems for human health and the environment. For example, microplastic is discharged into the atmosphere when fossil fuels are utilized as feedstock to create synthetic textile fibers, posing a threat to human health and ecology [6]. Adverse effects of cotton textiles include using pesticides, soil erosion, and irrigation with water [7]. Conversely, wool textiles have the potential to contribute up to 50 % of greenhouse gas (GHG) emissions without improper treatment [8]. Of the methods used to handle textile waste, 57 % include landfilling, 25 % involve incineration, 10 % involve recycling, and 8 % involve reuse each year [9]. Disposing of textile waste in landfills can lead to several issues, including scarce land, GHG emissions during decomposition, and hazardous substances like dyes leaching into the groundwater and soil [9]. In a global analysis of per capita landfilled textile waste generation, the United States and China emerged as the leading contributors, with 29.3 and 14.5 t, respectively [10]. Incineration can produce a lot of carbon dioxide and potentially hazardous substances, including benzene derivatives, particulate matter, and polycyclic aromatic

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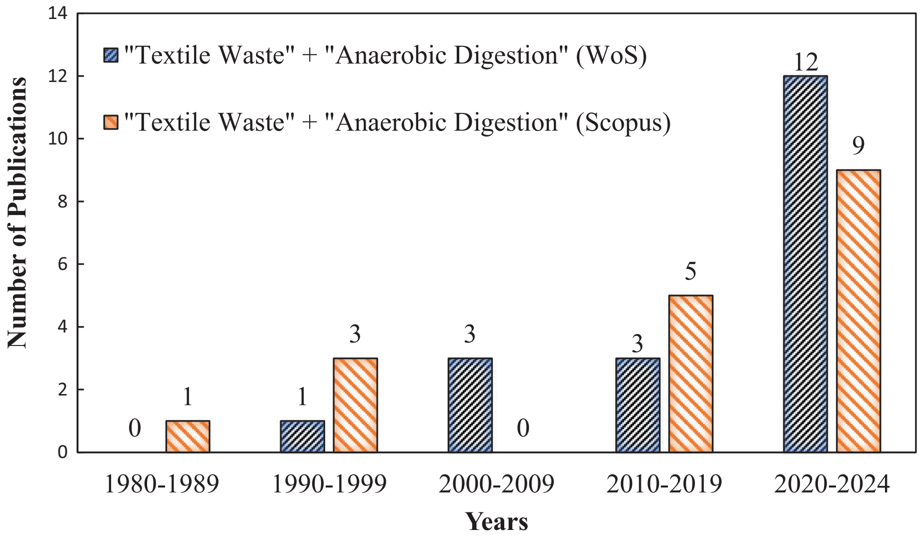


Figure 1. Number of publications characterizing "textile waste" + "anaerobic digestion" via Web of Science (WoS) and Scopus.

hydrocarbons [11]. Incineration also produces dioxin and furans, which cause health severity to humans. Recycling is an appropriate way to prevent textile waste from ending in landfills. As a sign of mitigation from hazardous textile waste management, it is converted into value-added products [12].

Textile waste valorization is a circular economy approach that provides various possibilities for extracting fibers from discarded textiles and creating value-added products. Regarding waste-to-energy valorization, several applications are available: incineration, pyrolysis, gasification, and anaerobic digestion (AD). By technology evaluation via the fuzzy TOPSIS method, Afrane et al. [13] ranks AD as the most feasible technology because of low capital cost, operational and maintenance cost, and carbon emission compared with other waste-to-energy technologies. Fiber's natural matter might be broken down into biogas and digestate via AD technology. The production of biogas is crucial to the environment as it has the potential to save 10–13 % of GHG worldwide [14]. Digestate from AD can be used as fertilizer for growing plants for environment-friendly farming due to its rich N, P, and K composition [15]. Sequential process phases can be used to characterize the microbiological processes of AD: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [16]. Natural fibers constitute cotton, wool, linen, and silk, whereas polyester, polyamide, acrylic fiber, and polypropylene are synthetic [17]. As AD is preferable for natural fibers, the focus will be on cotton and wool. Both cotton and wool are good sources of energy-recovery feedstocks [18]. The cotton content of textile waste has a high potential as feedstock to produce value-added products, such as ethanol and biogas, due to the high cellulose content of fibers but hindered by the crystalline structure [19]. On the other hand, wool is composed of abundant keratin, which is adequate for energy generation but challenging due to its high stability and low solubility [20, 21].

Fig. 1 highlights the number of publications from Scopus and Web of Science (WoS) on textile waste AD over the last decades. The research into textile waste AD is limited. Based on Scopus and WoS publications, only 18 and 19 articles were featured, respectively, for "textile waste" + "AD," which peaked at 8 and 12 research articles during 2020–2023. Serious consideration is currently being investigated by researchers on this matter due to its abundant generation and making sure that the textile waste can be treated sustainably without causing problems to the environment. AD is highly recommended in textile waste management for clean energy production to mitigate environmental issues [22].

Only a few studies have been published on AD specifically for textile waste. For example, Anacleto et al. [22], Alves et al. [23], Wojnowska-Baryła et al. [24], and Juanga-Labayen et al. [25] only discussed pretreatment methods applied to the textile waste AD process. All these reviews did not comprehensively review the challenges and other opportunities, specifically on textile waste. Understanding the challenges is fundamental for implementing AD textile waste process solutions. To the best of our knowledge, no review study deeply explored this area. Therefore, the main objective of this review is to rectify the challenges and possible solutions that hinder textile waste treatment and valorization via AD process. This review provides a comprehensive overview of the typical characteristics of textile waste and its potential applications in AD systems. The challenges associated with textile waste management and future strategies for optimizing AD processes are also discussed. Implementing tailored solutions to address the challenges specific to textile waste in AD processes will enhance biogas production efficiency and optimize the utilization of textile waste as a valuable resource for sustainable energy generation. In this way, environmental problems can be avoided, and textile waste minimization can be enhanced.

2 Characteristics of Common Textile Waste

Fig. 2 illustrates the categorization of textile fabrics, distinguishing between those derived from natural sources, including plants and animals, and those originating from artificial materials, further divided into organic and synthetic components.

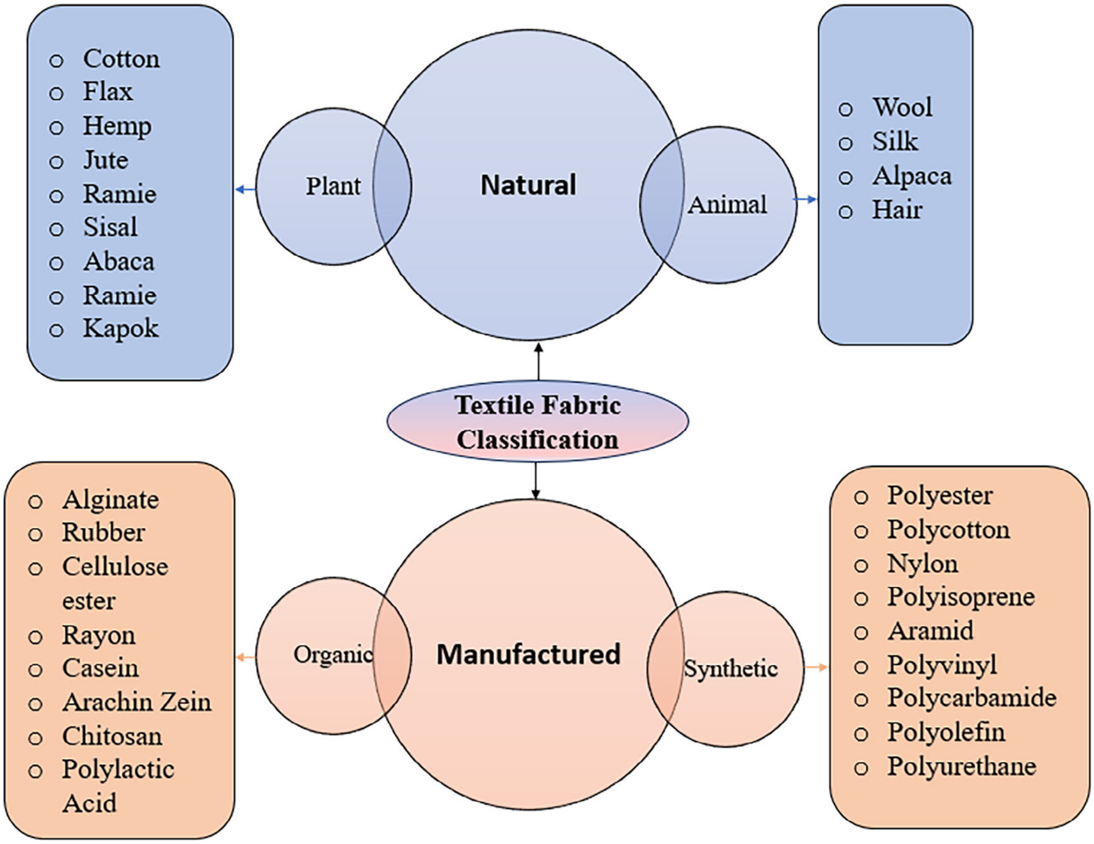


Figure 2. Textile fabric classification. *Source*: Modified from Ref. [26].

Three common textile wastes discussed in this context are cotton, wool, and polycotton, the major natural fiber utilization worldwide.

Tab. 1 depicts common textile waste component structure and physical and chemical properties. The physical part involves the component structure characteristic and calorific value, and the chemical properties include thermal degradation under thermogravimetric analysis (TGA) conditions, water affinity, chemical carbon-to-nitrogen ratio (C:N), carbon oxygen demand (COD), and pH. As can be seen in Tab. 1, similar characteristics among the common textile waste are neutral range pH, which is suitable for AD application on biogas production and digestate recovery [27].

2.1 Cotton

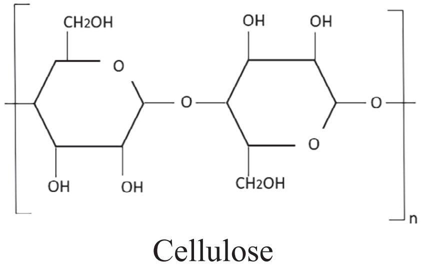
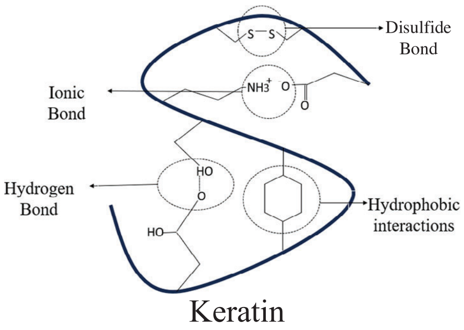
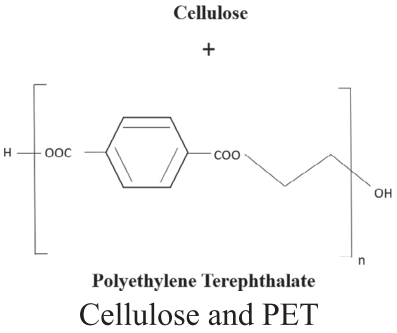
Cotton, a type of natural cellulosic fiber, is widespread in the textile industry. The fibers are harvested from the cotton ball that grows on plants belonging to the Gossypium hirsutism family [43]. Cotton fibers consist essentially of 95 % cellulose, mainly in the primary wall, winding layer, and secondary wall. The remaining 5 % of noncellulosic compounds are located primarily in the cuticle and primary cell wall and contain wax, pectic substances, organic acids, sugars, and ash-producing organic salts [44, 45]. Its chemical composition is 85.0–90.0 % cellulose, 1.0–3.0 % hemicellulose, 0.7–1.6 % lignin, and 0.8–1.8 % pectin [28].

The major structure of cotton textiles is cellulose, as shown in Tab. 1. From a physical perspective, cellulose structure consists of crystalline and amorphous regions. The crystalline parts are responsible for the required strength of the fiber, consisting of around 70–80 %; the rest are amorphous regions essential for elasticity, flexibility, and the ability of the fibers to absorb water, dyes, and chemical finishes [28]. In chemical studies, thermal degradation of cotton began with a weight loss of 5 % when the temperature was heated to 310 °C, which could be attributed to the loss of moisture. The second part of decomposition continues until 380 °C, which lost 81 % of its initial weight due to cellulose breakdown. Cotton lost 96.0 % of its initial weight at 600 °C [30, 46]. This shows that the thermal resistivity of cotton is high enough to break the cellulose bond. However, cellulose exhibits considerable promise for AD prospects due to its molecular composition, containing carbon and hydrogen atoms per molecule. This composition facilitates facile breakdown by microorganisms within the AD process [32].

2.2 Wool

Wool fiber is another source of organic material sufficient for AD. Australia, China, and New Zealand are the major contributors to wool waste [47]. Wool is chemically unique from cotton

Table 1. Physical and chemical properties of common natural textile.

Type of common textile	Major component structure	Physical properties	Chemical properties
Cotton		- Crystalline structure: Durability and tenacity [28] - Amorphous structure: Flexible [28] - Calorific value: 16.80 MJ kg^{-1} [29]	- Thermal degradation: >310 °C [30] - Water affinity: Hydrophilic [28] - pH: 7.1 [22] - C:N ratio: 98 [31] - COD: 2550 mg L^{-1} [22]
Wool		- Disulfide bond: Durability [32] - Hydrogen bond: Hydroscopic and elasticity [33] - Ionic bond: Tenacity [34] - Hydrophobic interaction: Hydrophobic [35] - Calorific value: 23.47 MJ kg^{-1} [36]	- Thermal degradation: >200 °C [37] - Water affinity: Hydrophobic [35] - pH: 7.9 [22] - C:N ratio: 2.6 [38] - COD: 2080 mg L^{-1} [22]
Polycotton		- TPA in PET: Durable [39] - EG in PET: Flexible [40] - PET calorific value: 24.13 MJ kg^{-1} [41]	- PET thermal degradation: >390 °C [30] - Water affinity: Semi-hydrophilic, PET is hydrophobic [39] - pH for PET: 6–8 [42]

and other plant fibers because it contains around 97 % protein and 3 % lipid [20]. Wool has a natural waviness known as "crimp," which adds to its insulating qualities. The surface of the fibers is composed of overlapping cuticles. Wool is a multipurpose fabric that may be used for clothing, carpets, rugs, socks, and even specific agricultural uses as fertilizers [48]. In addition, due to its nitrogen-rich content, it can serve as a viable and renewable biomass alternative for generating value-added products, such as biogas, via AD [49].

Wool fibers are robust protein fibers in the α-keratin fiber family [32], as the structure depicted in Tab. 1. α-Keratin consists of 80–85 % in protein structure [50], which existed in nails, claws, beaks, feathers, hair, and horns [30]. In physical terms, α-keratin peptide connections and a highly cross-linked network of disulfide bonds constitute cysteine amino acid, incredibly resistant to enzymatic and physical attacks, giving wool stability and anti-wrinkle strength [32]. Wool's protein comprises a polypeptide backbone, which has acidic carboxyl groups (–COOH) and amino acids ($–NH_2$), which provide elasticity and tenacity, respectively [46]. Disulfide, hydrogen, hydrophobic, and ionic bonds interact in the polypeptide backbone. The hydrogen bonds of these groups contribute to a hygroscopic nature that helps to absorb and retain moisture from the surrounding environment [33]. An ionic bond exists between ammonium cations and carboxylic anions, enhancing strength and stability [34]. As for chemical aspects, a hydrophobic structure is a nonpolar aliphatic ring that is highly water-resistant and insulated [35]. The thermal degradation of cotton began with the weight loss of 8 % when the temperature was heated to 100 °C, which could be attributed to the loss of moisture. The second part of decomposition begins at 200 °C. It continues until 450 °C, which lost 60 % of its initial weight due to destroying the lateral chain of wool protein molecules and releasing hydrogen sulfide and sulfur dioxide due to the cleavage of disulfide bonds. Finally, wool lost 95.0 % of its initial weight at 900 °C; the remaining are ashes [37].

2.3 Polyester

The world's most throwaway synthetic material is polyester. Clothes made of polyester are derived from oil-based polyethylene terephthalate (PET), a synthetic linear macromolecule in the chain at least 85 % by mass, created by combining ethylene glycol (EG) and terephthalic acid (TPA) [51, 52]. Although polyester is inexpensive, highly moldable, and nontoxic when applied topically, its nonbiodegradable nature poses a significant obstacle to AD [53]. In Tab. 1, for physical characteristics, TPA's existence in polyester structures is shrink-resistant and has exceptional strength and durability [39], and EG functions as flexibility for PET [40]. In terms of chemical characteristics, polyester is also a hydrophobic substance, which means it is challenging to absorb liquids due to the ester linkage formed between the carboxyl group (–COOH) of TPA and the hydroxyl group (–OH) of EG, causing nonpolar nature which inhibits water molecule attraction [39]. Usually, polyester melts and loses shape between 255 and 265 °C [54]. However, concerning the environmental aspects, heating polyester can produce toxic chemicals that can contribute to global warming, including particulate matter, nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and BTEX compounds (benzene, toluene, ethylbenzene, and xylene) [55].

The most common blended textile waste is polycotton, classified as polyester [56]. Polycotton, a synthetic material, is created by combining polyester fibers with cotton fibers during spinning, resulting in a fabric that blends properties from both materials [57]. Polycotton is most commonly used in hospitals and hotels because it combines the durability and wrinkle resistance of polyester with the comfort and breathability of cotton, which is suitable for large-scale use in settings that require frequent washing and a professional appearance [24]. However, recycling polycotton is challenging because cotton-based textiles are often blended with various ratios of polyester, making recycling difficult as the well-organized blending structure might prevent enzymes from forming cotton [24]. Blended cotton has an immense molecular weight and more inter- and intramolecular connections than unblended cotton because it has higher degrees of crystallinity and polymerization [58]. These factors may cause inhibition of AD degradation.

In the TGA context, moisture removal is the first stage of the thermal degradation of polycotton, which ends at 310 °C. Then, the cotton undergoes decomposition till the temperature range of 381–390 °C, influenced by the cotton content, typically falling within the percentage range of 35–60 %. After that, polyester starts to lose shape at 390 °C degrades till 470–485 °C [30]. The thermal degradation of polycotton requires a higher temperature compared with pure cotton because the polyester blend contributes high thermal resistance. In addition, a mixture of more polyester requires a higher temperature to degrade.

3 Textile Waste Anaerobic Digestion

AD is a biological process that breaks down organic matter without oxygen, producing biogas and a residue known as digestate [59]. Biogas is mainly composed of methane gas (50–75 %), carbon dioxide (25–50 %), and small nitrogen amounts (2–8 %) [60]. For biogas production via AD, mesophilic and thermophilic temperatures are vital for methanogen growth. When the temperature reaches 35–37 °C, it is classified as mesophilic; when it comes to 55–60 °C, it is classified as thermophilic [61]. Utilizing AD to valorize textile waste presents a compelling and environmentally responsible solution to promote sustainability within the fashion and textile industry.

Fig. 3 shows that AD has four pathways: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [16]. First, common textile waste (e.g., cotton, polycotton, and wool) consists of complex polymers converted to monomers through the hydrolysis process for efficient structure decomposition. In the initial stages of AD, the hydrolysis process facilitates the conversion of cotton and wool into their respective elemental components, yielding glucose from cotton and keratin from wool. Subsequently, during the acidogenesis and acetogenesis phases, microbial activity further breaks down these components, transforming them into volatile fatty acids (VFAs). The culmination of these processes leads to biogas production through methanogenesis, completing the intricate biochemical transformations in the AD system.

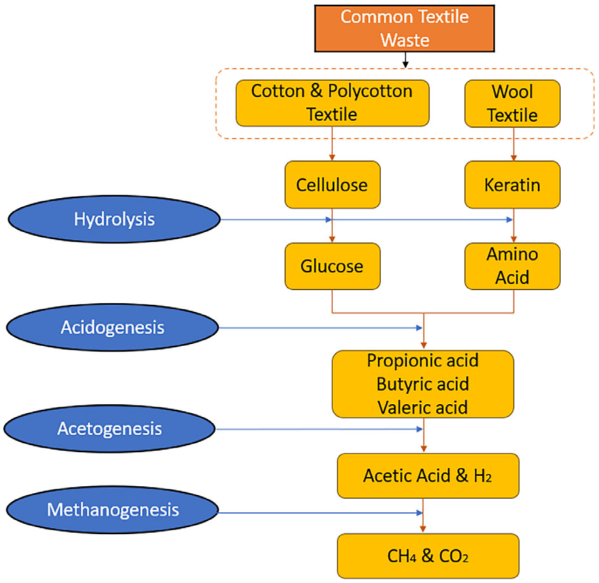


Figure 3. Common textile waste anaerobic digestion pathway.

4 Potential Valorization of Textile Waste by Anaerobic Digestion

4.1 Energy Recovery

Utilizing biogas may provide heat and power, and when it is further purified, it can create biomethane, which can be used as fuel for vehicles, cooking gas, and gas grid [62]. Tab. 2 describes the methane gas from various textile waste sources, including cotton, polycotton, and wool fabric. This study focuses on how cutting and grinding impact AD process efficiency.

Based on findings documented in Tab. 2 of the relevant literature about cotton fabric, the ground cotton waste with OLR of 5 g L^{-1} produces the highest methane yield of 653 mL g^{-1} VS because sufficient substrate loading benefits microbial degradation during the AD process [63]. Despite the findings of Jin et al. [31], it is observed that substantial cutting of cotton fabric and a high OLR of 10 g L^{-1} result in a twofold decrease compared with 5 g L^{-1}. This methane reduction is attributed to diminished volatile solid reduction and the toxic effects that hinder microbial activity. Raj et al. [64] experimented with 5 kg cotton, which produces methane gas of 28 mL g^{-1} VS only. This could be because extensive cellulose loading inhibits methane production. Another study shows that different total solid (TS) percentages affect methane production, where the lower TS provides significant methane yield due to the sufficient concentration loading, which enables efficient acetate solubilization. On the other hand, polyester produces the lowest methane compared to organic textile fabric due to the inhibition of microbial degradation [65]. Substrate-to-inoculum (S/I) also plays a vital role in cellulose breakdown. For example, Juanga-Labayen et al. [66] reported that a 0.5 S/I ratio produces the highest methane yield than 1.0, 1.5, and 2.0 because adequate loading substrate enables effective degradability. Another observation from Tab. 2 depicts that cutting fabric into smaller sizes contributes to positive methane results. For example, cutting cotton waste in squares length of 1.5 × 0.5 cm^2 has an increment of twofold in contrast with 2 × 2 cm^2 and 4 × 4 cm^2 due to larger surface area, allowing better microbial accessibility for substrate decomposition.

The concentration of cellulose also affects the methane contribution during the AD process. For example, Jin et al. [31] compared AD between cellulose fabric, which resulted in flax producing the highest methane yield (356 mL g^{-1} VS), and biodegradability of 78 % because its high cellulose content of 90 % maximized glucose recovery and low lignin percentage (1 %) enables efficient bacterial hydrolysis. However, blended fabrics contribute minimal methane due to their lower organic concentration, constraining methane conversion, particularly from acetate intermediates. For instance, blended textiles like cotton/polyester demonstrate a 21 mL g^{-1} VS reduction in methane yield compared to pure cotton. This decrease is linked to the lower cellulose content, impeding methane production [67]. Another experiment also showed that 60 % viscose blended textile has a higher methane yield than 50 % cotton blended [68]. This explicitly states that organic content affects methane yield production.

As for the wool fabric comparison, the thermophilic temperature grinding into a 2 mm size produces a methane yield of 22 mL g^{-1} VS [69]. However, grinding wool using mortar and pestle creates 87 mL g^{-1} of methane [70]. The reduced methane yield observed in thermophilically pretreated wool can be attributed to a 30 % blend of polyamide, a synthetic polymer, inhibiting methane production. In another case, by comparing TS concentration, wool with 1 % TS provides a significant methane yield of 122 mL g^{-1} VS with 14 times enhancement in contrast with 2 % TS due to the low substrate concentration enabling efficient acetate solubilization [65]. Nonetheless, Kabir et al. [49] also conducted with various TS contents of wool, and 21 % TS contributes to the highest methane yield (61 mL g^{-1} VS) compared to 6 %, 13 %, and 30 % because of better synergic effects of microbial activity to decompose the substrate. As a result, appropriate TS content is required for suitable microorganism breakdown to optimize methane production.

4.2 Digestate Recovery

AD also produces digestate in solid and liquid fractions. The current management practice uses digestate for land application as fertilizer or soil improver [74]. One can use the solid digestate leftovers from a biogas process as fertilizer [75–77]. The liquid digestate portion is unsuitable for use as fertilizer because of its inferior capacity for residual biogas, high COD, nitrogen leaching, and penetration into groundwater that could contaminate nearby rivers [78]. For example, in Tab. 1, the COD level of cotton and wool exceeds the fertilizer standard quality limit, that is, 200 mg L^{-1} [79], which is inadequate for direct application. AD has a high potential for COD removal, and the treated digestate is viable for fertilizer application [80]. Composting is relatable with AD digestate because of its similar function. The function of composting is converting waste into products such as bio-fertilizers and soil conditioners [81]. Composting has been studied on cotton and wool for fertilizer purposes

Table 2. Methane production from textile waste from anaerobic digestion.

Textile waste	Type of AD	Treatment condition	CH_4 yield of the textile waste	Refs.
Cotton Kapok Rayon White denim Blue denim Flax Ramie Hemp Jute Abaca Sisal	Continuous	S/I ratio: 1:1 Method: Cut into 2 × 2 cm^2 Loading rate: 10 g L^{-1} Operating temperature: 37 °C HRT: 50 days	Cotton: 343 mL g^{-1} VS Kapok: 295 mL g^{-1} VS Rayon: 327 mL g^{-1} VS White denim: 330 mL g^{-1} VS Blue denim: 160 mL g^{-1} VS Flax: 356 mL g^{-1} VS Ramie: 333 mL g^{-1} VS Hemp: 335 mL g^{-1} VS Jute: 318 mL g^{-1} VS Abaca: 266 mL g^{-1} VS Sisal: 327 mL g^{-1} VS	[31]
Cotton	Continuous	S/I ratio: – Method: Fine grinding Loading rate: 5 g/L Operating temperature: 38 °C HRT: 30 days	653 mL g^{-1} VS	[63]
Cotton	Batch	S/I ratio: – Operating temperature: 30–32 °C HRT: 50 days	28 mL g^{-1} VS	[64]
Cotton Linen Jute Silk Wool Polyester	Batch	S/I ratio: 1.6 Method: Cut into 4 × 4 cm^2 Operating temperature: 37 °C HRT: 40 days	TS 1 %: – Silk: 291 mL g^{-1} VS Wool: 122 mL g^{-1} VS Polyester: 0 mL g^{-1} VS TS 2 %: – Cotton: 105 mL g^{-1} VS Linen: 90 mL g^{-1} VS Jute: 100 mL g^{-1} VS Silk: 125 mL g^{-1} VS Wool: 9 mL g^{-1} VS Polyester: 0 mL g^{-1} VS TS 4 %: – Cotton: 14 mL g^{-1} VS Jute: 20 mL g^{-1} VS Linen: 82 mL g^{-1} VS	[65]
Cotton	Batch	S/I ratio: 1:10 Method: Cut into 2 × 2 cm^2 Operating temperature: 37 °C HRT: 40 days	200 mL g^{-1} VS	[67]
Jeans, 60/40 blended cotton and polyester	Batch	S/I ratio: 1:10 Method: Cut into 2 × 2 cm^2 Operating temperature: 37 °C HRT: 40 days	171 mL g^{-1} VS	[67]
50/50 blended polyester/cotton 40/60 blended Polyester/Viscose	Batch	S/I ratio: 10:1 Method: Cut into 3 × 3 cm^2 Operating temperature: 35 °C HRT: 3 days	Polyester/Cotton: 1 mL g^{-1} VS Polyester/Viscose: 8 mL g^{-1} VS	[68]
70/30 Blended Wool/Nylon 6	Batch	S/I ratio: 10:1 Method: Grinding into 2 mm size Operating temperature: 55 °C HRT: 46 days	22 mL g^{-1} VS	[69]
Wool	Batch	S/I ratio: 10:1 Method: Mortar and pestle grinding Operating temperature: 37 °C HRT: 40 days	87 mL g^{-1} VS	[70]

(Continued)

Table 2. (Continued)

Textile waste	Type of AD	Treatment condition	CH_4 yield of the textile waste	Refs.
Cotton	Batch	S/I ratio: 0.5, 1.0, 1.5, 2.0 Method: Cut into 1.5 × 0.5 cm^2 Operating temperature: 35 ± 2 °C HRT: 15 days	S/I 0.5: 367 mL g^{-1} VS S/I 1.0: 151 mL g^{-1} VS S/I 1.5: 48 mL g^{-1} VS S/I 2.0: 19 mL g^{-1} VS	[71]
A mixture of Malaysian natural textile fabric	Continuous	S/I ratio: 1:2 Method: Cut < 1 cm Loading rate: 10 g/L Operating temperature: 37 °C HRT: 35 days	174 mL g^{-1} VS	[72]
Medical cotton	Batch	S/I ratio: 1:10 Operating temperature: 35 °C SRT: 131 days	13 mL g^{-1} VS	[73]

due to its richness in macronutrients and good biodegradable material, which improves soil fertility. No research was conducted on textile waste AD digestate analysis for bio-fertilizer application.

The process of composting is an aerobic way of breaking down organic waste. This is a critical method of recycling organic waste to create beneficial fertilizers [82]. An experiment has been conducted on vermicomposting cotton textiles, which are rich in carbon content and have helped generate energy for worms, which can effectively be consumed as a carbon source to make a mature, healthy compost [83]. Wool also offers a good application for fertilizer usage due to the help of suint, a wool grease released from the roots of the wool fibers. The thread has a high concentration of macronutrients, particularly potassium (K) of 33 000 mg kg^{-1}, making it appropriate for bio-fertilizer application for quality growth and yield of agronomic crops [38, 84]. Composting successfully sanitizes waste and produces organic fertilizers through stabilizing organic waste; it is a better option for promoting circular agriculture [85].

Blended textiles, such as polycotton (a combination of polyester and cotton), pose a risk of soil and groundwater contamination by releasing microplastics, rendering them unsuitable for fertilizer application [86]. The polyester is broken down into monomers, which can be recycled back to the original material, known as monomer recovery. Notwithstanding, the remaining polyester suitable for AD can be ideal for post-treatment (e.g., pyrolysis and gasification) for energy recovery due to higher calorific value compared with conventional coal [87, 88]. This section only has information about composting from direct textile waste. However, the digestate from AD can also be applied as fertilizer except for synthetic, which is improper for fertilizer usage.

5 Challenges of Textile Waste Substances for Anaerobic Digestion

5.1 Carbon-to-Nitrogen Ratio

The C:N ratio is one of the determining constraints for the effective digestion of substrate and biogas production. The ideal C:N ratio for AD ranges from approximately 20:1–30:1. Extremely high or low C:N ratios could inhibit the methanogenic population and hence methane generation rate, which would favor the accumulation of VFAs and ammonia in the digestion solution [89]. For common textiles, cotton and wool do not meet the ideal C:N ratio range for AD. The C:N ratio of sheep wool waste is 2.62, which falls below the optimum range for biogas production, potentially leading to the accumulation of ammonia [38]. On the other hand, cotton has a C:N ratio of 98, which is considerably high, as shown in (Tab. 1). This elevated ratio in cotton can contribute to the accumulation of VFAs during AD [31]. These variations in C:N ratios highlight the importance of considering the feedstock composition in AD processes, as it can significantly impact the efficiency and byproducts of biogas production.

5.2 Blended Synthetic Fibers

Blended synthetic fibers, especially polyester, are nonbiodegradable, which inhibits microbial breakdown during AD. For example, a study was conducted where the untreated jeans and cotton produced methane of 171 and 200 mL g^{-1} VS, respectively [67]. Another study by Juanga-Labayen and Yuan [90] concluded that cotton had higher biogas and methane yields than polycotton, with 272 and 250 mL g^{-1} VS values, respectively. These experiments indicate that polycotton produces less biogas than pure cotton due to undegradable polyester inhibiting methane production. Blended cotton has higher degrees of crystallinity and polymerization than unblended cotton due to the blended cotton's higher molecular weight. This makes it more difficult for microorganisms to break down the fibers, resulting in lower biogas production [58].

Polyester in blended fabric releases microplastic fibers, a significant source of environmental problems. Microplastics are frequently released while washing clothes. Research has found that 1 g of polyester textile can produce microplastics ranging from 4900 to 640 000 microplastics with a size between 10 and 20 µm, which is a significant issue to resolve [91]. Polyester in textile waste, mainly composed of PET, affects the AD process. PET microplastic causes inhibitory effects to prevent microbial breakdown. For direct mechanism, microplastics result in microbial cell disruption and death. Polyester develops, creating

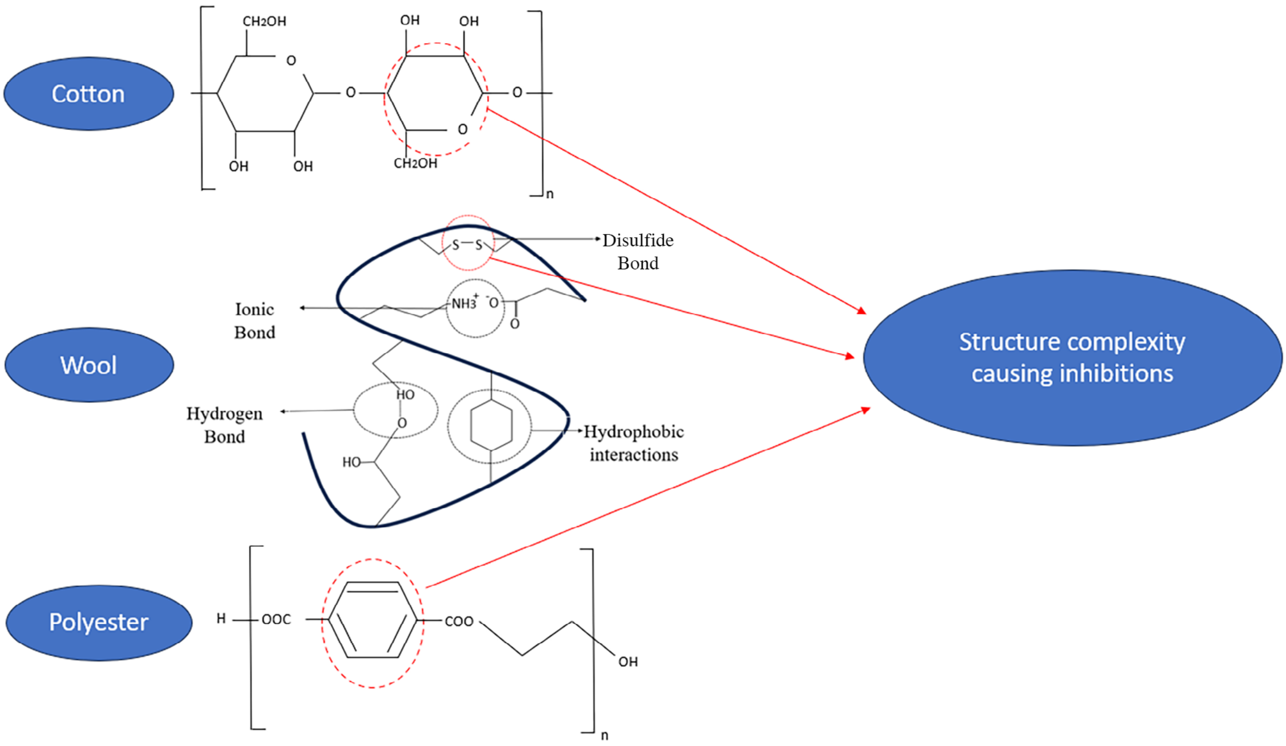


Figure 4. Structure recalcitrant of cotton, wool, and polyester affecting the performance of anaerobic digestion.

reactive oxygen species that interrupt microbial activity, reducing biomass viability during AD. In contrast, PET, a widely used polymer under the polyester family for textile manufacturing, produces dibutyl phthalate for indirect mechanism. This toxic chemical inhibits hydrolysis, acidogenesis, acetogenesis, and methanogenesis processes. PET microplastics also impact the antibiotic resistance genes (ARGs) to AD microbial, which increases the abundance of eight various ARGs such as tetracycline, sulfonamide, Mex, and erythromycin that results in methane generation inhibition [92].

5.3 Structure Complexity

Cotton, wool, and polyester textile waste have several structural complexities, and they are highly resistant to chemical structure breaking and inhibiting microbial degradation during AD. Fig. 4 illustrates the structure recalcitrant of cotton, wool, and polyester, which inhibit the AD process.

One could argue that cotton is the purest natural source of cellulose [93]. Cotton's crystalline structure contributes to a high 72 % crystallinity index and inhibits microbial breakdown for methane conversion [31, 65]. For example, during AD, *N*-methylmorpholine-*N*-oxide (NMMO) pretreatment examined the solubilization rate of regenerated cellulose (amorphous cellulose) and cotton linter (crystalline cellulose). The maximum solubilization rates of treated cellulose were 842 and 517 mg COD (g COD day)$^{-1}$, which increased by 102 % and 24 %, respectively. In contrast to the amorphous cellulose, which influences solubilization, the high crystalline cellulose required a more extended period before digestion began. The high rate of hydrolysis, which is detrimental to the remainder of the process and inhibits the activity of microorganisms doing acetogenesis/methanogenesis, was the direct cause of the difference between the two forms of cellulose [94].

Wool compromise of keratin-rich by-products has also been reported as suitable substrates for AD [70]. This particular property of keratin constitutes an obstacle in AD in achieving sufficient microbial degradation, which results in a low methane yield due to disulfide bridges and other intermolecular interactions [95]. This is shown in Tab. 2 when comparing the methane yield of carbon and protein-rich fabric at 2 % TS; wool contributes to a lower methane yield of 9.13 mL g^{-1} VS compared to other cellulose fabric due to the existence of disulfide bridges, which inhibit acetate solubilization during acetogenesis process [65].

Polycotton, which consists of polyester and is the most widely utilized synthetic fiber, is deemed unsuitable for AD processes due to its limited susceptibility to significant microbial degradation, essential for efficient biogas production [65]. Polyester comprises PET with TPA, an aromatic benzene ring with high crystallinity that prevents microbial decomposition [96]. The ester bonds in TPA are challenging to break, and the hydrophobic nature makes it hard for microorganisms to access the polymer. Azcona et al. [65] describe that polyester did not produce biogas due to no significant degradation during AD.

Table 3. Dyes used in textile materials [103].

Dye category	Applicability
Reactive	Cotton, linen rayon, wool, silk, polycotton
Disperse	Nylon, acrylic, polyester, polycotton
Direct	Cotton, linen, rayon, wool, silk, polycotton
Acid	Silk, wool, nylon
Basic	Acrylic, rayon

5.4 Dye Recalcitrant

Some of these compounds are toxic and recalcitrant, which can inhibit the AD process, such as aromatic amines generated from degrading dyes with substantial toxicity, mutagenicity, carcinogenicity, and low biodegradability which is challenging for removal purposes [97–99]. Textile dye comprises heavy metals like lead (Pb), chromium (Cr), cadmium (Cd), and copper (Cu) in the form of color pigments [100]. Heavy metals indirectly influence AD by affecting microorganisms, whereas concurrently, the determining factors in AD, including temperature, pH, ammonia nitrogen, and material ratio, contribute to the transformation of heavy metal speciation [101, 102].

Tab. 3 describes the dyes applicable to the textile category [103]. There are various types of dyes (e.g., reactive, dispersed, direct, acid, and basic). The most commonly used dye in the textile industry comprises reactive dyes due to color fading resistance [104, 105]. Reactive dyes are widely used for natural textile fabric for cotton and wool because they chemically bond with the fibers, providing excellent color fastness with covalent bonds in hydroxyl and amino groups, respectively [106]. Direct dyes are also applicable because they have a natural affinity for these fibers, allowing for a more straightforward dyeing process without additional chemicals [107]. Acid dyes are suitable for wool because they form strong ionic bonds with the amino groups in the protein structure of wool fibers, resulting in durable and vibrant coloration [107]. Disperse dyes are well-suited for polyester due to their compatibility with the hydrophobic nature of the fiber. Their low water solubility, stability at high temperatures, and ability to undergo sublimation make them efficient for coloration in polyester via the H-bond and van der Waals force present in TPA, allowing for even and durable results [108]. Reactive, dispersed, and direct dyes are suitable based on polycotton dye's applicable ability. However, applying these dyes on fabric may inhibit microbial degradation for biogas production because of the presence of heavy metals.

6 Solutions to Textile Waste Anaerobic Digestion

6.1 Pretreatment

The main objective of the pretreatment method is to hydrolyze the cotton and wool complex structure, which increases substrate accessibility for biogas production. In addition, pretreatment can degrade synthetic material that exists in blended fibers. Different pretreatment methods, including physical, chemical, thermal, and biological approaches, exert varied influences on improving AD and methane production [109]. Physical, thermal, chemical, and biological pretreatment methods have been applied to textile waste to improve biomethane potential (BMP). Tab. 4 discusses the significant enhancement of methane after the pretreatment of textile waste.

Grinding was experimented on wool textile waste with liquid nitrogen for physical pretreatment, resulting in an 80 % increment of methane gas after pretreatment [70]. Grinding wool waste with a liquid nitrogen additive reduces particle size and enhances solubility and bioavailability for dipeptide bond decomposition.

In the chemical pretreatment context, alkali is widely used compared with acid due to the contribution of more methane yield, as shown in Tab. 4. Na_2CO_3 with 0.5 M is used chiefly for cotton and polycotton textiles, which diminished methane improvement by 103 % and 92 % at the optimum temperature of 150 °C [67, 71]. This fact is because of the mercerization effect by sodium carbonate, which gives the cotton fiber a swollen appearance with a silky luster and causes a significant change in the crystalline structure of cellulose [110]. However, for wool-sourcing waste, the application of NH_4Cl has a poor effect on the dipeptide bonds in the cysteine structure due to a lack of reducing agent properties [111]. Ionic liquid (IL) is considered an efficient direct solvent for cellulose materials and can be utilized for the chemical reprocessing of cotton. Applying an IL, specifically NMMO, as a pretreatment agent on polycotton substrates has enhanced cotton recovery better than viscose. Viscose contributes to lower methane yield generation due to its semisynthetic composition, which inhibits decomposition. The blended polycotton treatment has proven effective in significantly augmenting methane yield, increasing by 1.3×10^4 % [68]. In addition, Jeihanipour et al. [112] also conducted another experiment on jeans composed of 100 % cotton with a similar NMMO pretreatment method, which resulted in doubling the methane production from the untreated substrate due to a highly accessible surface area for cellulose fiber decomposition in jeans.

Biological pretreatment methods involving enzymes and bacteria have exhibited notable advancements, showcasing substantial improvements in the overall process. Both enzymes and bacteria pretreatment have produced good biomethane for textile waste. Alkaline endopeptidase is suitable for wool pretreatment, which enhanced the methane yield by 274 % during the 50-day digestion period [49]. In addition, *Clostridium sensu stricto*, a bacterium, has satisfactory accessibility to textile waste degradation and can produce (>50 % BMP) cellulose textile waste [31].

In thermal pretreatment, the wool textile subjected to autoclaving at 120 °C, positioned within the high-temperature spectrum, manifests the most substantial enhancement in methane gas production up to 10-fold relative to alternative pretreatment methods. This outcome is attributed to elevated soluble chemical oxygen demand, facilitating the breakdown of complex organic compounds into simplified, soluble forms conducive to enhanced microbial digestion and improved biogas and methane yields [113].

Table 4. Pretreated textile waste effect on methane production.

Pretreatment	Technique	Textile waste	AD type and condition	Treatment condition	CH_4 yield		Changes in BMP [%]	Refs.
					Untreated	Treated		
Physical	Grinding	Wool textile	Type: Batch Temp.: 37 °C HRT: 40 days	Liquid N_2	87 mL g^{-1} VS	157 mL g^{-1} VS	+80	[70]
Chemical	Alkali	Cotton textile waste	Type: Batch Temp.: 35 °C HRT: 15 days	0.5 M Na_2CO_3, 150 °C, 3 h	151 mL g^{-1} VS	307 mL g^{-1} VS	+103	[71]
	Alkali	Jeans containing polyester and cotton (60/40)	Type: Batch Temp: 37 °C HRT: 40 days	0.5 M Na_2CO_3, 150 °C, 2 h	171 mL g^{-1} VS	329 mL g^{-1} VS	+92	[67]
	Acid	Cotton yarn	Type: Batch Temp.: 35 °C HRT: 30 days	2 % H_3PO_4 140 °C, 2 h	–	278 mL g^{-1} VS	–	[114]
	Acid	Wool scouring wastes	Type: Batch Temp: 35 °C HRT: 35 days	NH_4Cl	300 mL	266 mL	−11	[111]
	Ionic liquid	50/50 blended polycotton 40/60 blended poly-viscose	Type: Batch Temp.: 35 °C HRT: 3 days	85 % NMMO, 120 °C, 3 days	Polycotton: 1 mL g^{-1} VS Poly-viscose: 8 mL g^{-1} VS	Polycotton: 131 mL g^{-1} VS Poly-viscose: 128 mL g^{-1} VS	Polycotton: +13 000 Poly-viscose: +1500	[68]
	Ionic liquid	Jeans (100 % cotton)	Type: Batch Temp.: 55 °C HRT: 30 days	85 % NMMO, 120 °C 3 days	180 mL g^{-1} VS	360 mL g^{-1} VS	+100	[112]

(*Continued*)

Table 4. (Continued)

Pretreatment	Technique	Textile waste	AD type and condition	Treatment condition	CH_4 yield		Changes in BMP [%]	Refs.
					Untreated	Treated		
Biological	Enzyme	70/30 blended Wool/Nylon 6	Type: Batch Temp.: 37 °C HRT: 50 days	Alkaline endopeptidase	35 mL g^{-1} VS	131 mL g^{-1} VS	+274	[49]
	Bacteria	Cotton Kapok Rayon White denim Blue denim Flax Ramie Hemp Jute Abaca Sisal	Type: Continuous OLR: 10 g L^{-1} Temp.: 37 °C HRT: 50 days	*Clostridium sensu stricto*	Cotton: 195 mL g^{-1} VS Kapok: 168 mL g^{-1} VS Rayon: 193 mL g^{-1} VS White denim: 189 mL g^{-1} VS Blue denim: 112 mL g^{-1} VS Flax: 200 mL g^{-1} VS Ramie: 193 mL g^{-1} VS Hemp: 193 mL g^{-1} VS Jute: 193 mL g^{-1} VS Abaca: 159 mL g^{-1} VS Sisal: 200 mL g^{-1} VS	Cotton: 343 mL g^{-1} VS Kapok: 295 mL g^{-1} VS Rayon: 327 mL g^{-1} VS White denim: 330 mL g^{-1} VS Blue denim: 160 mL g^{-1} VS Flax: 356 mL g^{-1} VS Ramie: 333 mL g^{-1} VS Hemp: 335 mL g^{-1} VS Jute: 318 mL g^{-1} VS Abaca: 266 Sisal: 327 mL g^{-1} VS	Cotton: +76 Kapok: +76 Rayon: +70 White denim: +75 Blue denim: +43 Flax: +78 Ramie: +73 Hemp: +74 Jute: +65 Abaca: +67 Sisal: +64	[31]
Thermal	Autoclave	Cotton textile	Type: Batch Temp.: 37 °C HRT: 40 days	Autoclave 120 °C, 10 min	158 mL g^{-1} VS	204 mL g^{-1} VS	+29	[67]
	Autoclave	70/30 Blended Wool/Nylon 6	Type: Batch Temp.: 55 °C HRT: 46 days	Autoclave 120 °C, 10 min	22 mL g^{-1} VS	210 mL g^{-1} VS	+855	[69]
Combined methods	Physical + chemical	Cotton waste	Type: Continuous OLR: 5 g L^{-1} Temp.: 38 °C HRT: 30 days	Physical: Micro-aeration Acid: H_2SO_4	653 mL g^{-1} VS	247 mL g^{-1} VS	−62	[63]
	Thermal + biological	70/30 blended Wool/Nylon 6	Type: Batch Temp.: 55 °C HRT: 46 days	Thermal: Autoclave, 120 °C, 10 min Biological: Alkaline endopeptidase, 55 °C for 8 h	22 mL g^{-1} VS	430 mL g^{-1} VS	+1855	[69]
	Thermal + chemical	Cotton textile	Type: Batch Temp.: 35 °C SRT: 90 days	Thermal: Autoclave, 120 °C, 20 min Chemical: Ca $(OH)_2$	13 mL g^{-1} VS	18 mL g^{-1} VS	+38	[73]

Three categories of combined pretreatment methodologies have been executed, encompassing (i) physical and chemical, (ii) thermal and biological, and (iii) thermal and chemical processes. The physical and chemical pretreatment uses micro-aeration and sulfuric acid to reduce the biomethanation by 62 % [63]. The cause may be due to the inefficiency of acid accessibility in breaking the bonds and the micro-aeration process that limits oxygen penetrations to break the hydrogen bonds of crystalline structure. Notwithstanding, autoclaving and alkaline endopeptidase improve the methane yield up to 430 mL g^{-1} VS during thermophilic AD because of the grinding effect, which enhances the surface area of the substrate for effective pretreatment [69]. The findings suggest a substantial increase in solubilization through the combined impact of autoclaving and enzymatic reactions, leading to effective cysteine degradation and elevated methane levels. In addition, autoclaving with $Ca\ (OH)_2$ shows a significant increment of methane, around 38 %, compared with untreated cotton medical waste, which is both thermally and alkali-effective for cotton degradation. Despite improvement in methane recovery, methane yield is relatively low, with 18 mL g^{-1} VS consequences of large fabric size, inhibiting hydrolysis [73]. The statement above is deemed acceptable compared to individual methodologies, as discussed above.

Recommendations for pretreatment technologies are provided based on textile waste composition. For cotton-rich waste streams, alkali treatments (Na_2CO_3), thermal pretreatment (autoclaving), and IL pretreatment are effective methods, with NMMO IL showing significant improvement in methane yield but requiring feasibility assessment. For wool-rich waste streams, biological pretreatments (enzymes and bacteria) and thermal pretreatment (autoclaving), particularly the combination of autoclaving and alkaline endopeptidase, demonstrate promising synergistic effects in addressing the recalcitrant nature of wool waste. When pretreating blended textile waste, NMMO IL or a combination of thermal and biological methods can be considered for optimal methane production. Overall, thermal pretreatments showed great results for all textile waste compositions. To optimize methane yield and overall process efficiency, the precise composition and features of the waste must be taken into consideration while choosing pretreatment procedures. Thorough evaluations of scalability, cost-effectiveness, and environmental impact are also necessary.

6.2 Co-Digestion

Anaerobic co-digestion is the digestion of two or more substrates with complementary characteristics, which shows better performance and is expected to provide better nutrient balance and biogas production than mono-digestion [115]. Anaerobic co-digestion is beneficial to optimize fabric C:N ratio balance, which can lead to a more stable digestion process and recalcitrant removal from the textile dye. However, the inappropriate ideal range C:N ratio of cotton and wool affects biogas production due to high concentrations of cellulose and keratin, respectively—lack of research conducted on co-digesting textile waste. Therefore, a comparison was undertaken, wherein similar substrates, including cotton gin trash, cotton stalks, cellulose for cotton fabric, and chicken feathers for wool textiles, were employed [116, 117].

Tab. 5 indicates the co-digestion of textile waste and identical feedstock to achieve optimal methane production. Overall, the 50:50 blending ratio of substrates was most applied, contributing to a positive methane impact. For cotton textile comparison, identical substrates, such as cotton gin trash, cotton stalk, and cottonseed, were co-digested with manure, which composes 80–90 % organic content, enabling efficient microbial breakdown [118]. The co-digestion of cotton gin trash with cow dung enhances methane production to 370 mL g^{-1} VS [119]. Goat manure is a suitable co-substrate for cotton waste, which achieved a BMP result of 55 % [120]. Cheng and Zhong [121] reported the highest by comparing similar substrates, as shown in an increment of 120 % methane thanks to the C:N ratio, which is in the range of optimum biomethanation, a C:N ratio of 25, which proves the theory. However, Venkateshkumar et al. [122] explained that cotton seed hull is inappropriate to co-digest with cow dung because cotton seed hull has a low biodegradability rate, low nutrient content, and high lignin content, which makes the microorganism indigestible. Li et al. [113] confirmed that cellulose inhibits methane production when co-digested with lignin compared with hemicellulose to support this statement. Co-digestion of cellulose and lignin indicates negative methane enhancement due to the inaccessibility of microorganisms for cellulose hydrolysis. Cotton textiles present a more favorable substrate for biogas production than high lignin content substrates, owing to their lower lignin concentration. This characteristic enhances the accessibility of microorganisms, promoting more efficient biogas production processes.

Wool textile co-digested with carbon-rich substrate may contribute to high methane yield. For example, wool co-digested with wheat straw, a carbon-rich substrate with a 50:50 mixing ratio, significantly increases methane production by 186 %. TS with 13 % results better than 6 %, 21 %, and 30 % because of sufficient microbial activity for methane enhancement [49].

In another case, anaerobic co-digestion can also reduce heavy metals from fabrics. For example, the experiment was conducted on textile dye sludge (TDS), the wastewater from the industry after the dyeing process. In a different study, the ideal mixing ratio of 1:1 with soybean okara produced 503 mL $CH_4\ (g\ VS)^{-1}$, an increase of 15.6 %; COD removal was achieved at a rate of 64 % and considerable reduction in heavy metals (Zn, Cu, Cr, and Ni) compared to TDS alone [123]. This study has not been tested on textile fabric, which also has a high potential for recalcitrant reduction.

6.3 Separation of Synthetic Material from Blended Textile

Separating synthetic material from polycotton is vital for biogas production because it results in efficient energy recovery. For example, cotton waste from polycotton can produce biogas through AD [126]. Chemical pretreatments are discovered to separate synthetic materials from blended fabric efficiently.

For example, an environment-friendly cellulose solvent, NMMO, was used to separate and pretreat cotton from blended fabric. This solvent was mixed with polycotton at 120 °C and

Table 5. Co-digestion of natural textile and identical properties of various substrates.

Textile waste	AD condition	Optimal mixing ratio	AD type	CH_4 yield of the treated textile waste	Changes in BMP [%]	Refs.
Co-digestion of cotton gin trash and cow dung	S/I ratio: 1:4 Temp.: 37 °C HRT: 91 days	50:50	Batch	Before co-digestion: 210 mL g^{-1} VS After co-digestion: 370 mL g^{-1} VS	+76	[119]
Co-digestion of a cotton stalk and swine manure	S/I ratio: 4:1 Temp.: 35 °C HRT: 21 days	50:50	Batch	Before co-digestion: 102 mL g^{-1} VS After co-digestion: 224 mL g^{-1} VS	+120	[121]
Co-digestion of cotton gin trash and goat manure	S/I ratio: 1:4 Temp.: 36 °C HRT: 62 days	30:70	Batch	Before co-digestion: 170 mL g^{-1} VS After co-digestion: 206 mL g^{-1} VS	+21	[120]
Co-digestion of cellulose (C) with hemicellulose (H) and lignin (L)	S/I ratio: 1:1 Temp.: 35 °C HRT: 35 days	50:50	Batch	Before co-digestion: 251 mL g^{-1} VS After co-digestion: C + H: 262 mL g^{-1} VS C + L: 95 mL g^{-1} VS C + H +L: 159 mL g^{-1} VS	C + H: 4 C + L: −62 C + H + L: −37	[124]
Co-digestion of cotton seed hull and cow dung	S/I ratio: – Temp.: 35 °C HRT: 45 days	25:75	Batch	Before co-digestion: 193 mL g^{-1} VS After co-digestion: 83 mL g^{-1} VS	−57	[122, 125]
Co-digestion of wool and wheat straw	S/I ratio: 2:1 Enzyme: alkaline endopeptidase, cellulolytic enzyme Temp.: 37 °C HRT: 50 days	50:50	Batch	Before co-digestion: 35 mL g^{-1} VS After co-digestion: 100 mL g^{-1} VS	+186	[49]

atmospheric pressure to isolate the cellulose from the undissolved noncellulosic fibers. After separating synthetic polymer from jeans, the cotton produces methane of 361.1 mL g^{-1} VS, which is an enhancement of 111 % compared with unseparated textiles [67]. Another example is sodium carbonate (Na_2CO_3), an alkali medium commonly applied in removing impurities, mercerization, and other processes for the preparation of cotton fiber in the textile industry, which was used in this process for separation and pretreatment of the cellulose. This alkali medium significantly reduces the cellulose crystallinity of lignocellulose. After separating cotton from blended textile at 120 °C for 2 h, the methane yield rose by 80 % compared with untreated fabric [68].

New research has been conducted on betaine-based deep eutectic solvents (DESs), an environment-friendly solvent first synthesized and innovatively used to degrade PET fibers from polycotton blends selectively. As a result, PET fiber was degraded completely, a purified monomer bis(2-hydroxyethyl terephthalate) with a yield of 85 % was obtained that could be depolymerized to produce PET, and 95 % of the cotton was recycled and maintained its original structural integrity [127]. Unfortunately, no AD testing was conducted for this DES. This method can be applied as an alternative source for AD to improve methane yield. This method can be used to investigate the AD process further.

6.4 Dye Removal

Dye removal from fabric may result in biogas improvement through the AD process. Multiple studies have been conducted on dye removal, such as physiochemical, biological, advanced oxidation processes (AOPs), and AD. Ismail and Sakai [103] reviewed that AOPs have high effectiveness in dye removal, no toxic byproduct, and ease of operation compared with other methods but, unfortunately, have a high-cost drawback. AOPs consist of ozone, Fenton, photocatalytic, and photo-Fenton processes. Oxidizing agents such as ozone (O_3), hydrogen peroxide (H_2O_2), and permanganate (MnO_4) are commonly applied in AOPs to facilitate the destruction or decomposition of dye molecules in textile waste [128]. AOPs have been rapidly developed to degrade contaminants that cannot be removed biologically, such as trace organic dyestuff from the textile industry [129]. For example, biochar derived from nano-MnO [130] and almond shell [131] integrated with AOP has the ability to remove heavy metals like Cu(II), which exist in dyestuff [132]. In addition, Ding et al. [133] concluded that ultra-violet (UV)/H_2O_2 has a removal of 96 % of rhodamine B dye compared to H_2O_2 alone, which is negligible [134]. Hama Aziz and Mustafa [132] reported a notable increase of 643 article publications in AOP research for heavy metal removal from 2013 to 2023. This surge in publications underscores the growing relevance and recognition of

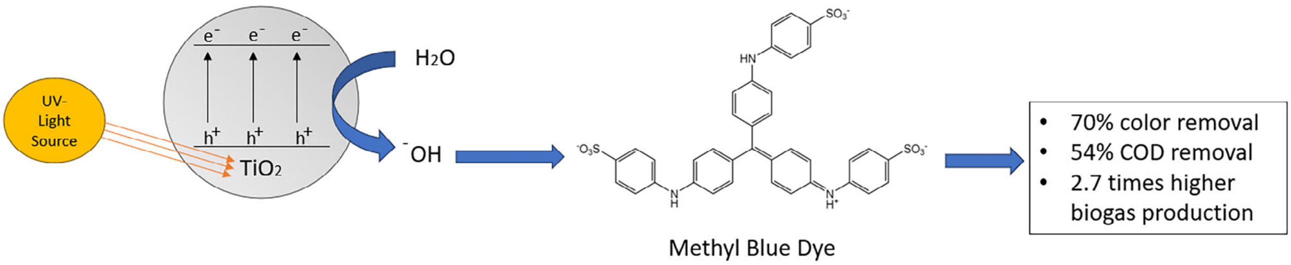


Figure 5. Mechanism of methyl blue (MB) dye degradation via UV-light assisted advanced oxidation process (AOP). *Source*: Modified from [137].

AOP as a treatment technology for addressing the removal of impurities.

Due to AOPs' effectiveness in dye removal, only this technology has been tested for its efficacy in biogas production through dye removal. So far, only one study has been conducted on textile dye removal's effect on biogas production. An example of UV photocatalyst pretreatment has been conducted on dye oxidizing for biogas production on methyl blue (MB) dye, commonly used for dyeing cotton and wool fabrics [135]. In this case, zeolite was used as a support material for bioreactors and photocatalysts to enhance dye removal for microorganisms and photocatalysts. AD can only remove 32 % of the dye, but UV/TiO_2 photocatalysis has a better effectiveness of 70 % removal due to reactive hydroxyl radicals ($^{*}OH$) helping to degrade the dye. According to the results, biogas production increased 2.7 times when MB with AD underwent pretreatment photocatalysis compared to MB without pretreatment [136]. At optimum pretreatment conditions, this study shows improvement in biogas yields, which was much higher for the undyed fabric consequences of impurities present in the dye, which impede the AD process. Fig. 5 illustrates the mechanism of UV/TiO_2 degrading MB dye for biogas enhancement.

7 Conclusion

AD technology has significant potential as an effective option for textile waste management due to its benefits in cost and environmental perspective. Current methods, such as landfills and incineration, result in severe environmental problems from textile waste properties. This study comprehensively reviews the challenges of textile waste using AD. To enhance the processability, solutions, such as pretreatment techniques, co-digestion strategies, and polyester/dye removal, could significantly enhance biogas production from pure and blended textile materials. Overall, most of the studies have been conducted with pretreatments technologies due to high efficacy. The study recommends further research optimizing AD processes for textile waste, as well as techno-economic and environmental impact assessments evaluating the feasibility of producing biogas and bio-fertilizers on a commercial scale. It proposes that enhancing the AD of textile waste can create value-added products, addressing global textile waste issues through sustainable solutions.

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Abbreviations

AD	Anaerobic digestion
AOP	Advanced oxidation process
ARG	Antibiotic resistance genes
BMP	Biomethane potential
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
C:N	Carbon to nitrogen ratio
DES	Deep eutectic solvent
GHG	Greenhouse gases
HRT	Hydraulic retention time
IL	Ionic liquid
MB	Methyl blue
OLR	Organic loading rate
PET	Polyethylene terephthalate
SRT	Solid retention time
S/I	Substrate-to-inoculum ratio
TDS	Textile dye sludge
TGA	Thermogravimetric analysis
VFA	Volatile fatty acid
TS	Total solid
UV	Ultra-violet
VS	Volatile solid

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