Sustainable Utilization of Synthetic Nonwoven Waste Materials (NWM) for Improving Clay Soils in Rural Road Construction in Tanzania: A Review Paper

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DOI: https://doi.org/10.47772/IJRISS.2026.10200622

Received: 02 March 2026; Accepted: 09 March 2026; Published: 23 March 2026

ABSTRACT

The rapid growth of plastic production and consumption has significantly increased the generation of synthetic nonwoven waste materials, creating serious environmental and waste management challenges. In parallel, the need for sustainable ground improvement techniques in geotechnical engineering has intensified. This study presents a structured literature review evaluating the potential application of synthetic nonwoven waste materials as soil reinforcement agents. Following the PRISMA 2020 framework, 54 publications were initially identified, of which 15 studies met the inclusion criteria for detailed analysis.

The reviewed studies consistently demonstrate that incorporating small percentages (0.2–1.5% by dry soil weight) of synthetic nonwoven fibers significantly enhances key geotechnical properties. Reported improvements include increases in unconfined compressive strength of up to 64%, substantial gains in California Bearing Ratio (CBR) values, reductions in plasticity index, and notable decreases in swelling potential. These improvements are primarily attributed to mechanical interlocking, frictional resistance, and crack-bridging mechanisms provided by randomly distributed fibers within the soil matrix.

The findings indicate that synthetic nonwoven waste materials offer a technically viable and environmentally sustainable alternative to conventional chemical stabilizers, particularly for subgrade and embankment applications. Moreover, this approach aligns with circular economy principles by diverting textile waste from landfills while enhancing soil performance. Although global studies confirm the effectiveness of synthetic fiber reinforcement, limited research has examined its application within the Tanzanian context. Therefore, further experimental investigations are recommended to evaluate locally available nonwoven waste materials and establish design guidelines for practical implementation.

Keywords: Geosynthetics; Nonwoven Waste materials (NWM); Nonwoven geotextiles; Soil stabilization; Synthetic fibres; Polypropylene stabilization; Clay reinforcement

INTRODUCTION

Clayey soils present significant challenges in geotechnical engineering especially in rural roads construction due to their high plasticity, low shear strength and pronounced sensitivity to moisture fluctuations (Mhando & Kamlenga, 2025). Generally, their plasticity indices range high and their bearing capacities differ from when wetted and when dried (Kalantari, 2012). These soils are mostly found in arid and semiarid areas and contain large amount of clay minerals (Mhando & Kamlenga, 2025). In Tanzania, this challenge often results in premature pavement failures, high maintenance costs and short service life of road infrastructure (Vincevica-gaile et al., 2021; Mhando & Kamlenga, 2025). Traditional stabilization methods such as mechanical stabilization and chemical treatments (cement or lime) have been widely used in road construction (Al-Tabbaa & Stegemann, 2005). These methods can be costly and environmentally challenging due to CO_2 emissions during their production, high energy consumption and resource depletion compared to the use of waste and recycled materials (Krishna, 2024). Geosynthetics, particularly nonwoven geotextiles manufactured from polypropylene (PP) and polyester (PL), have been recognized as effective and environmentally preferable alternatives for improving weak subgrade soils (Ogundare et al., 2018). Nonetheless, commercial geotextiles remain costly and energy-intensive to produce, thereby limiting their widespread application in rural areas (Ramjiram Thakur et al., 2021; Kimarai, 2023). Consequently, there is increasing emphasis on adopting circular economy approaches that promote the reuse of waste materials while reducing environmental impacts (Basu et al., 2013). The increasing amount of plastic and synthetic waste (especially in developing countries like Tanzania) has driven researchers to seek alternatives that are innovative and sustainable on reusing or recycling it (Dahale et al., 2012). In Tanzania there is growing solid waste management challenges due to urbanization, with about 0.44 kg of waste generated per person per day, of which around 20% is non-biodegradable synthetic waste (Kuderer, 2022; Wagh et al., 2019). Therefore, alternative solutions that reduce environmental impact while ensuring soil stability, performance and cost-efficiency are needed (Kimarai, 2023).

Following the 2019 plastic bag ban in Tanzania, nonwoven polypropylene bags rapidly replaced conventional plastics, increasing the accumulation of non-biodegradable synthetic waste, with about 99.5% ending up in landfills or open burning (NEMC, 2019; Greene, 2011). Also, synthetic nonwoven waste materials made of PP and PL from textile scraps, shopping bags, industrial packaging films, agricultural fabrics and medical disposables (bags, gloves, face masks, surgical gowns etc.) have gained attention as a potential solution because of their effectiveness in acting as containment and its availability (Kopitar et al., 2022; ACERETECH-Machinery, 2025; Tang et al., 2025). Globally, synthetic fibres account for about 75% of the 100 million tons of annual fibre production (Ellen MacArthur Foundation, 2017; Sajous, 2022), while polypropylene represents around 18% of global polymer production (Antolinc & Filipič, 2021), contributing to rising nonwoven textile waste. This growing availability of synthetic waste presents an opportunity to reuse nonwoven materials as sustainable alternatives for soil stabilization in rural road construction (Geyer et al., 2017; Wagh et al., 2019). This review critically examines global evidence and evaluates its relevance within the Tanzanian context.

From literature review out of 54 identified studies, 15 studies were in-depth reviewed and identified opportunities in repurposing synthetic nonwoven waste materials particularly made of PP and PL because these same polymers used in production of nonwoven geotextiles used in road construction (Xu et al., 2024; Ogundare et al., 2018; Ahmed, 2020). Also, from the literature review, previous studies have demonstrated that synthetic materials like polypropylene fibres, waste plastic bags, discarded textile fibres, synthetic waste cloth, textiles, COVID-19 disposable face masks (all of which contain nonwoven polymeric components) enhanced soil strength, compaction characteristics and overall geotechnical performance when incorporated with optimal contents between 0.2% and 1.5% by weight (Tiwari & Tiwari, 2016; Upreti et al., 2018; Barzoki et al., 2024; Alsadey & Salem, 2016; Ponnusamy et al., 2024). Findings from a thorough literature review highlight the potential of synthetic waste materials in improving Compaction, CBR and UCS when integrated with weak soil in the form of shredded fibres (Wagare et al., 2021; Bamrele et al., 2019), or confinement bags (Xu et al., 2024) but there is limited research on specific application of synthetic NWM (made of the same PP and PL) found in Tanzania in improving engineering properties of clayey soil found in Tanzania. Therefore, due to the identified potentials of synthetic NWM, investigation on its engineering implications when integrated into clayey soils from Tanzania is essential and need to be studied.

LITERATURE REVIEW

Background and Problem Statement

In Tanzania, clayey and expansive soils especially black cotton soils create major challenges for road and building construction (Mhando & Kamlenga, 2025). These soils change volume dramatically with moisture as they swell when wet and shrink when dry (Kumar et al., 2024). This constant movement can cause the ground to shift, leading to uneven settling, heaving, cracks, and surface problems in roads and building foundations if not managed properly (Kalantari, 2012). Field manifestations such as wide surface cracks during dry seasons and extreme stickiness during wet periods complicate construction and transportation activities (Kalantari, 2012). In laboratory classification, expansive soils in Tanzania commonly fall under CL–CH (USCS) and A-6 to A-7 (AASHTO) groups (Mhando & Kamlenga, 2025) . Their swelling behavior poses serious risks to pavements, foundations, and earth structures, increasing maintenance costs and reducing service life (Kumar et al., 2024). Consequently, expansive soils remain one of the major geotechnical hazards affecting infrastructure development in Tanzania (Lucian, 2006), hence necessitating effective soil improvement and stabilization strategies before using it in construction.

Synthetic Nonwoven Materials: Types, Characteristics and Production in Tanzania

Nonwoven materials are fabric materials typically made from synthetic polymers such as polypropylene and polyester (Sayed & Parte, 2015). Nonwoven fabric formation is highly emerging technology for production of cheapest material of textile for different purposes such as in garments, home textiles, decorative purposes and technical textiles (Senthil & Punitha, 2017). Nonwoven products are taking the place of many woven and knit materials because of their lower cost and lighter weight. Generally, the major area in nonwovens can be divided into disposal products such as diapers, sanitary wipes and napkins and durable products such as materials for apparel, home building packaging and industrial applications (Sayed & Parte, 2015). Also, these materials are durable and resistant to abrasion and used in textile scraps, carry bags, packaging films, agricultural fabrics and medical disposables (Sayed & Parte, 2015; Sumo, 2024).

Also, as defined by standards such as ISO 9092 and endorsed by international organizations like European Disposables and Nonwovens Association (EDANA), nonwovens are manufactured sheets made from directionally or randomly oriented fibres bonded through mechanical, thermal, or chemical methods without needing to form yarn (Cheema et al., 2018). These fibres, which range from short cellulose to long synthetic filaments provide a wide variety of material properties. Unlike paper or felt, nonwovens do not rely on hydrogen bonds or traditional wet-milling for processing (Albrecht et al., 2003). Their structure and performance heavily depend on the choice of raw materials, web formation methods (dry laid, wet laid, or polymer-based systems like spunbond or meltblown) and the consolidation process used (Cheema et al., 2018). Initially developed as low-cost alternatives that utilized industrial waste or limited resources, nonwovens have transformed into high-performance materials used in many sectors including hygiene, healthcare, automotive, construction, filtration, and agriculture. Despite their origins and the ongoing misconceptions of being low-quality or disposable, nonwovens are now recognized for their versatility, engineered functionality, and cost-effective solutions in both disposable and durable applications (Albrecht et al., 2003). Figure 1 shows structural differences between knitted, nonwoven and woven fabrics.

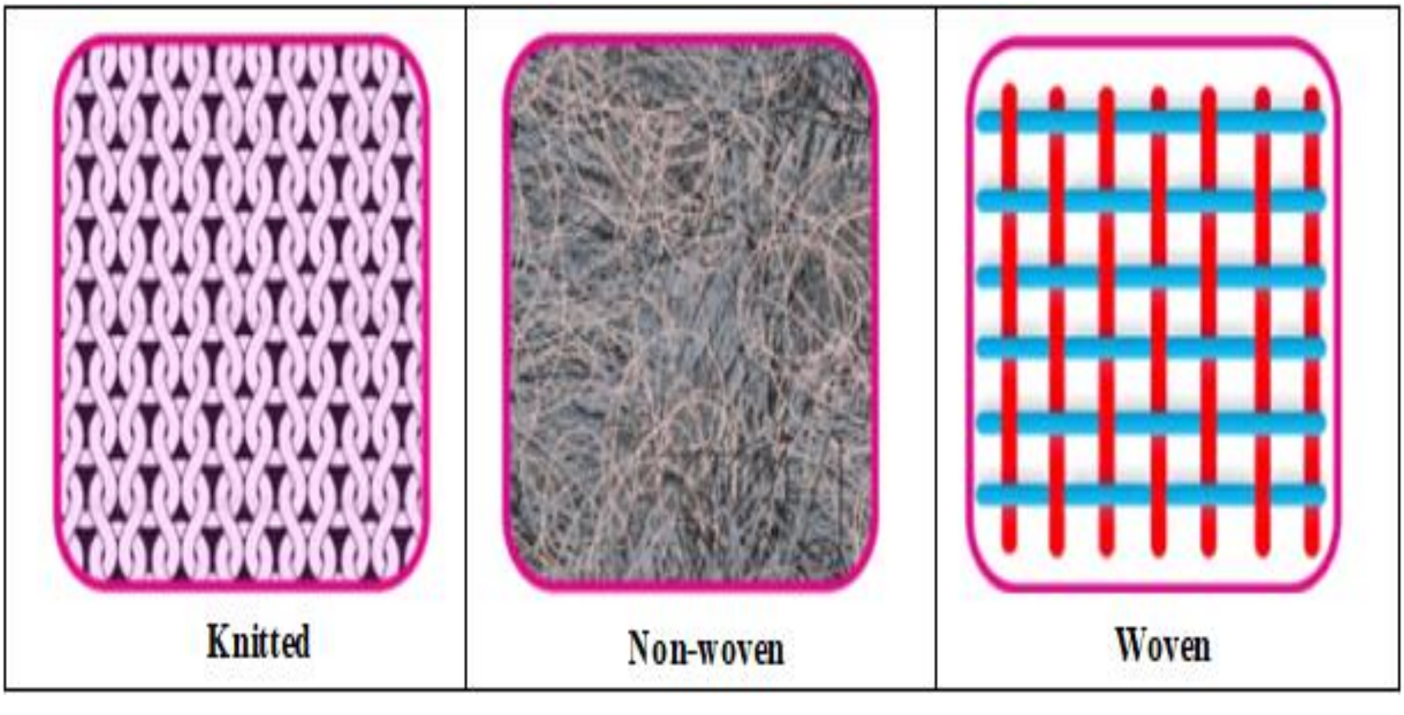

Figure 1: The structural differences between nonwoven and woven fabrics

Types and Classification of Nonwoven Materials

There are various types of nonwoven materials and each type of nonwoven can be made from different types of fibres (Senthil & Punitha, 2017). The type of fibre determines whether a nonwoven material is biodegradable or not. In most cases (over 90 % as of 2012) nonwoven bags are made up of spun bond polypropylene one of type of fibre which is not biodegradable (Wagh et al., 2019). Nonwoven materials come in various types, each suited to different applications based on their unique properties. Spunbond is lightweight, durable, and commonly used in products like medical gowns, diapers and filters. Meltblown nonwovens feature fine fibres with high filtration efficiency, making them ideal for face masks and industrial filters. (Senthil & Punitha, 2017) Needle-punched fabrics are thick and durable, often used in carpets, automotive interiors and insulation due to their resistance to tearing and wear (Sayed & Parte, 2015). Finally, Hydroentangled (Spunlace**)** nonwovens are soft and flexible, making them suitable for personal care products like wipes and medical applications. Each type of nonwoven material is designed to provide specific performance benefits across various industries (Albrecht et al., 2003).

Nonwoven Production and Waste Generation in Tanzania

According to EDANA 2010 Statistics, the European nonwovens industry (Europe, Turkey and a few significant Russian producers) produced around 1.78 million tons of nonwovens in 2010. The developed nations of North America, Western Europe and Japan currently represent nearly 60% of the global market for nonwoven fabrics (Gaminian et al., 2024). World consumption of fibres in nonwoven production is 60 % polypropylene, 23 % polyester and 8% viscose rayon, 2% acrylic, 1.5 % polyamide and 3% other high performance fibres (Ammayappan et al., 2006). However, such a large sector produces a large amount of waste, including production line waste and consumer waste. However, crucially part of the chemically treated nonwoven waste is disposed of by burying or burning, which leads to the possible formation of environmentally hazardous materials (EDANA, 2010). Nonwoven fabric production in Tanzania is primarily focused on manufacturing nonwoven bags, especially PP (Polypropylene) nonwoven bags and its related products. TC Industries Limited is a key player, producing a wide range of bags for various applications, including agro-bags, mesh bags, and FIBC (Flexible Intermediate Bulk Container) bags (NEMC, 2019). Nonwovens are an essential part of the fibre industry, competing with conventional textiles such as woven or knitted fabrics, paper, and board products, and they are forecasted to expand to a market value of USD 53 billion by 2030 (Gaminian et al., 2024). Nonwoven fabric imports to Tanzania are also significant, with a large number of shipments of nonwoven bags recorded, particularly in the period from October 2023 to September 2024, according to Volza.com (Volza, 2025). Nonwovens are the most rapidly expanding segment in the textile industry with hundreds of ends uses and product niches, not only as disposable products but also in more valuable non-disposable products. However, a critical knowledge gap persists due to public misperception of nonwoven material components, resulting in severely micro(nano)plastics (MNP) pollution (Tang et al., 2025). Current efforts remain insufficient to address this emerging environmental challenge, highlighting the urgent need for an assessment of their environmental impact and the development of sustainable solutions (Tang et al., 2025).

Synthetic Nonwoven Waste Materials (NWM) as Sustainable Soil Stabilizers

Waste Management Potential of Synthetic Materials in Clay Soil Improvement

Nonwoven waste materials refer to the discarded, unused or end-of-life nonwoven fabrics and products that are no longer needed. Sayed & Parte (2015) identified potentials of recycling nonwoven fabric waste from different sources such as medical gown, napkins, tissue paper, diapers, sanitary wipes and other disposable products. Managing nonwoven waste is a growing concern due to its large volume, non-biodegradability and the environmental challenges associated with its disposal (EDANA, 2010). Nonwoven fabrics continue to be one of the fastest growing segments in the textile world. It accounts for over 50% of the total textile activity in many developed countries (Albrecht et al., 2003). The tremendous growth in usage of nonwoven is mainly due to the variety of applications, which is backed by low cost of production due to very high productivity (Albrecht et al., 2003).

Synthetic nonwoven waste materials such as textile scraps, packaging waste and disposable nonwoven bags are one of solid wastes made of polymers which are non-biodegradable (Wagh et al., 2019) and are a growing component of Tanzania's waste stream (NEMC, 2019). Despite their availability and potential, over 99% of these materials are currently dumped/burnt and contributing to pollution and wasting resources (Greene, 2011). Globally, the accumulation of such waste continues to rise and large amount of it is disposed of in landfills (Sayed & Parte, 2015). The dumping of plastic waste including nonwoven wastes in landfills contributes significantly to global greenhouse gas emissions during degradation and lifecycle processes (Geyer et al., 2017). Due to the potential rise in plastic usage and dumping, its waste management is gradually becoming a top priority (Geyer et al., 2017) hence can be used for soil improvement while reducing environmental pollution in Tanzania.

Textile-Based Nonwoven Waste for Clay Soil Reinforcement

The textile industry has witnessed a significant shift from natural to synthetic fibres, primarily due to their cost-effectiveness (Kuderer, 2022). The growing demand for synthetic textile fibres can be attributed to several interrelated factors, including global population growth and the rising affluence of emerging economies, which drive higher consumption of textiles (Ellen MacArthur Foundation, 2017). Increased awareness of hygiene, particularly in the context of disposable products like towels and wipes, also contributes to the demand (Sumo, 2024). Moreover, the expansion of technical textiles, used in sectors ranging from healthcare to automotive and construction, further accelerates the need for these fibres (Lee et al., 2013). Textile waste in Africa can be divided into two main categories pre- consumer and post-consumer textile waste (Sumo, 2024). The pre-consumer waste is waste from the production process resulting from fabrics and garment samples, excess stock, fabrics from the end of rolls, or materials discarded and post-consumer textile waste consists of garments or household textiles that consumers no longer need and are ready to be discarded because they are worn out, damaged, or out of fashion (European Environment Agency, 2019). Waste generated during the textile manufacturing process such as cutting scraps from clothes often contains synthetic fibres such as polyester and nylon are non-biodegradable and contribute to textile waste, which is growing globally (Sumo, 2024). Also, nonwoven fabrics made from polyester and nylon are common in the textile industry and can often be found as waste (Wagh et al., 2019).The extent of the various textile waste streams is challenging to determine due to the incomplete data situation. Also, the lack of awareness to the people in this area restrict reuse and recycling options for textile waste and hinder sound ecologically-friendly disposal (Kuderer, 2022). Nonwoven fabric is one of the most innovative and promising categories for the textile industry since it currently utilizes about 66% synthetic materials (Gaminian et al., 2024).

The average Municipal Solid waste generation in Dar es Salaam increased by approximately 80 tons every year from 2006 – 2017 and it is estimated that by 2031, the amount of MSW generated will be more than 6400MT per day (Kuderer, 2022). While the amount of textile waste generated is estimated that make up around 2% of the total MSW composition (NEMC, 2019). Figure 2 is the photos of nonwoven textile scraps/wastes.

Figure 2: Examples of nonwoven textile scraps (pre-consumer and post-consumer waste)

The reviewed studies indicate strong potential for using textile waste to improve clay soils, which is highly relevant for Tanzania where expansive clays and low-bearing capacity subgrades are prevalent in rural road construction. Bamrele et al. (2019) studied on improvement of weak soil by using synthetic waste clothes and found that 1% synthetic waste clothes improved CBR of the soil (Bamrele et al., 2019). Guzman & Payano (2023) on their research found that polyester textiles from discarded clothing at 0.75% – 1.0% of poorly graded sand improved CBR from 18.1% to 32.4%. Also, Bitumen-coated waste cotton clothes fibres mixed by 1% of expansive soil improved MDD and increased CBR by 35.7% which can reduce pavement thickness (Wagare et al., 2021). Eshghi et al. (2025) investigated the mechanical behavior of clay reinforced with varying amounts of recycled carpet waste (RCW) and found 1% RCW reduced the maximum dry unit weight from 17.8 kN/m³ to 17.2 kN/m³ but increased the unconfined compressive strength improved up to 1% RCW, rising from 174.7 kPa to 216.7 kPa (Eshghi et al., 2025). Therefore, studies show there is a great potential in synthetic nonwoven textile wastes that can be found in Tanzania since are most effective due to their low moisture absorption and high tensile strength.

Packaging-Derived Polypropylene Waste for Soil Stabilization

Nonwoven packaging materials, such as bags made from polypropylene are widely used in consumer goods packaging (Wagh et al., 2019; Mahesh et al., 2020). The increasing use of nonwoven polypropylene bags for shopping and packaging contributes significantly to synthetic waste, resulting in severely micro(nano)plastics (MNP) pollution and highlighted the urgent need for an assessment of their environmental impact and the development of sustainable solutions (Tang et al., 2025).

After ban on plastic in Maharashtra state of India, different types of nonwoven polypropylene bags were produced and distributed as an alternative to plastic bags by shop owners which at first glance look like cotton bags, but Wagh et al. (2019) studied on its biodegradability and found that it contain polypropylene which are non-biodegradable and concluded that it should not be used as an alternative to the plastic bags (Wagh et al., 2019; Mahesh et al., 2020). The same situation in Tanzania after the ban of plastic bags in 2019, nonwoven bags introduced as ana alternative to replaced plastic bags to reduce environmental pollution but nonwoven bags once disposed in landfills has almost the same environmental effects as that of plastic bags since are non-biodegradable (Mahesh et al., 2020; Tang et al., 2025). In Tanzania before introducing nonwoven bags about 350,000 tons of plastic bags were produced every year (NEMC, 2019). After the ban of plastic bags, nonwoven bags replaced a significant portion of this usage, estimating that 10-20% of the original plastic bag usage, which is about 35,000 to 70,000 tons of nonwoven bags are being used annually in Tanzania. According to Volza's Tanzania Import data, Tanzania imported 415 shipments of Nonwoven Bags during the period from October 2023 to September 2024. These imports were supplied by 99 foreign exporters to 125 Tanzania buyers, marking a growth rate of 33% compared to the preceding twelve months (Volza, 2025). Since there is limited recycling facilities for nonwoven bags wastes in Tanzania (NEMC, 2019) nonwoven bags at their end use still contribute to waste accumulation, similar to plastic bags (Mahesh et al., 2020). Also, NEMC conducting study to check the biodegradability of nonwoven bags to ensure environmental and quality standards. Figure 3 shows synthetic nonwoven wastes from carry bags.

Figure 3: Nonwoven bag waste scrap, and nonwoven bags introduced in Tanzania after the plastic ban

Studies indicate that packaging materials and nonwoven polypropylene (PP) products particularly waste plastic bags and fibres have strong potential for improving weak soils in Tanzania while also addressing Tanzania's growing plastic waste management challenge.

Synthetic nonwoven shopping bags are made of polypropylene (PP) and polyester (Wagh et al., 2019) and according to various studies have found that Polypropylene (PP) fibres has a great performance in reinforcing weak soil hence nonwoven waste bags can be shredded into fibres and used the same. Upreti et al. (2018) in their study found that Synthetic Polypropylene (PP) fibres of 12mm length improved clay soil properties when mixed at 1%, whereby increased MDD from 1.64 g/cm³ to 1.70 g/cm³ and UCS from 15.19 N/cm2 to 19.21 N/cm2 (Upreti et al., 2018). Tiwari and Tiwari (2016), proved that addition of 0.5% polypropylene fibres (PPF) to soil increases its specific gravity by 0.3%, decreased the liquid limit of the soil by 18.18%, and the plastic limit also dropped by 12% (Tiwari & Tiwari, 2016). Also, in study of Iravanian and Ali (2020) a silty sand (A-2-4 soil) reinforced with 10 different Polypropylene plastic bags and observed that the value of CBR increases with increase in weight of plastic Bags.

Another study conducted by Xu et al. (2024) used Polypropylene soilbags of size (40 cm × 40 cm × 10 cm) to confine locally available excavated soft soil using a model tests and a 100 m field application and found that soilbag treated subgrades exhibit enhanced strength, stiffness and drainage with rapid pore pressure dissipation and uniform settlement. Also, shredded plastic shopping bags has shown significant enhancement of engineering properties with optimal performance at about 0.3% plastic content and fibre dimensions of 10 – 15 mm width and 40 mm length (Ahmed, 2020). Similar effects were observed when using LDPE plastic strips in soft clay, where improvements in CBR and stiffness were achieved (Dutta et al., 2009). Also, other studies used industrial nonwoven PP geotextiles in improving properties of weak soil. Industrial nonwoven PP geotextiles have been shown to substantially increase CBR of lateritic and clay soils, especially when placed near the base layer, enabling reduced pavement thickness and construction costs (Ogundare et al., 2018).

Medical and Hygiene Nonwoven Waste in Soil Improvement Applications

Disposable medical products like surgical gowns, bandages and face masks often contain nonwoven materials which are non-biodegradable (Tang et al., 2025) and once used, these materials are typically discarded by burning or dumped to landfill (Ponnusamy et al., 2024). Recent studies demonstrate strong potential for using medical and hygiene nonwoven waste materials particularly disposable face masks made of polypropylene as sustainable stabilizers for weak soils (clayey and expansive soils).

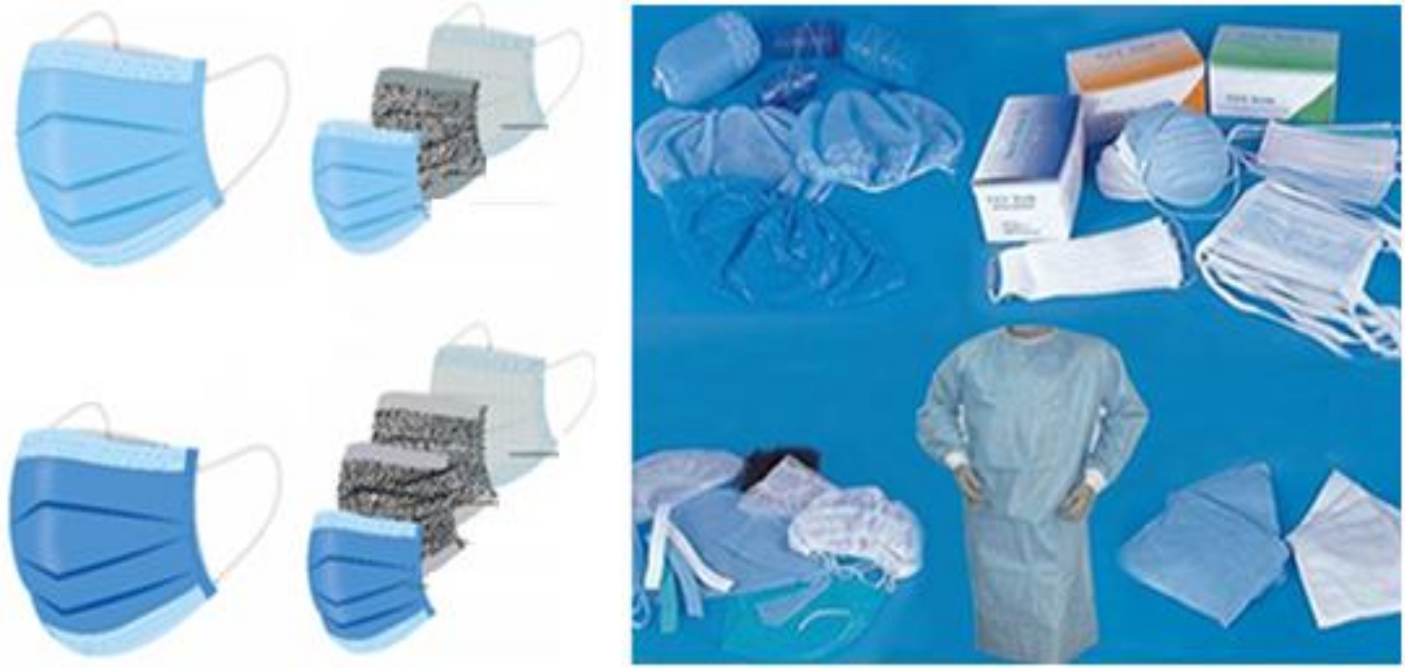

Figure 4: Disposable face masks and medical gowns which are predominantly polypropylene-based and represent an emerging waste stream post-COVID-19.

Watako (2023) explored reusing shredded single-use surgical face masks (SUSFM), one of nonwoven wastes in C30 concrete. SUSFM fibres (5 mm wide, 20 – 40 mm long) were added at 0 – 3% by cement mass and results showed that SUSFM reduced density and workability but increased water absorption. It also enhanced abrasion resistance due to crack bridging effects, while maintaining good overall quality (Watako, 2023). Other study done by Ponnusamy et al. (2024) found that 0.5% Shredded face masks improved strength and stability of expansive clay soils (Ponnusamy et al., 2024). Chandan and Sharma (2023) used Shredded face masks (SFM) to improve properties of clay soil and found that incorporating 1% SFM in clayey soil enhances its strength, with UCS improving by up to 64% after 28 days of curing and CBR increasing from 1.96% to 6.72% (Chandan & Sharma, 2023). Also, another study showed addition of 0.4% banana fibre and 1.5% waste face mask increases Maximum Dry Density (MDD) from 1.066 g/cc to 1.42 g/cc and improved UCS from 0.977 kg/cm² to 1.066 kg/cm² (Shobana et al., 2021). Since disposable face masks are one of nonwoven materials and the studies show that it can improve weak soil so it finds the way to look on potentials of medical and hygiene nonwoven wastes to improve properties of clay soil in roads construction in Tanzania, supporting sustainable infrastructure development, reducing environmental pollution, and lowering construction costs through waste valorization.

Processing and Application Techniques of Synthetic NWM for Soil Stabilization

From the literature, synthetic materials made of polymers (polypropylene (PP) and polyester (PET)) are one of the plastic category (Senthil & Punitha, 2017) in which at their end use are disposed and can lead to environmental pollution as they are non-biodegradable (Wagh et al., 2019). Also, polypropylene and polyester are commonly used in the manufacture of nonwoven geotextiles used for stabilization of weak soil in roads construction (Xu et al., 2024; Ogundare et al., 2018; Ahmed, 2020). Also, there are various studies proved the effectiveness of polypropylene fibres and plastic bags in improving properties of weak soil in roads constructions (Tiwari & Tiwari, 2016; Upreti et al., 2018) and in concrete strength (Alsadey and Salem, 2016). Literature also, shows some studies which used synthetic waste cloth (which is in form of nonwoven) in improving the properties of clay soil which demonstrated good performance in improving strength (Bamrele et al., 2019). From the identified potential of using NWM in improving properties of clay soil, the literature demonstrates that the integration of NWM can be done by shredding it into fibres for soil reinforcements (Watako, 2023; Shobana et al., 2021) and using it as a geotextile bags (confinement packages) in confining weak soil (Xu et al., 2024; Iravanian & Ali, 2020) as follows:

Fibre Shredding and Random Mixing with Soil

The reviewed literature demonstrates uniform reinforcement where the nonwoven waste material is shredded into fibres and thoroughly mixed with soil as the most preferred option. This ensures a more uniform distribution of reinforcement (Wagare et al., 2021; Bamrele et al., 2019). Experimental studies suggest that optimal proportions range between 0.2% and 1.5% by weight (Shobana et al., 2021; Barzoki et al., 2024), depending on the type of soil and reinforcement configuration (Barzoki et al., 2024).

Confinement Systems Using Nonwoven Soilbags

For confining purposes (simulating geotextile use in roads or embankments), wrapping or placing nonwoven bags intact in layers is generally preferred. This method simulates how nonwoven geotextiles are used in actual applications to provide confinement and prevent soil settlement to improve properties like compaction, load-bearing capacity and strength (Xu et al., 2024). This process uses the principles derived by Ogundare et al. (2018) where studied the performance of nonwoven geotextile sheets at depth of H/4 from the top and H/4 from the base where H/4 from the base provided good results. Using this principle in designing small uniform soil packages/Soilbags to form three-dimensional confinement and testing at depth of H/4 from the top, Mid-depth, H/4 from the base and Multiple layers (Ogundare et al., 2018). The study conducted by Xu et al. (2024) shows that when soil confined into bags can significantly enhance both the strength and deformation modulus of the soft soil. Bags can be in uniform size or small bags be placed over the large bags layer and gaps left will be filled by soil then compacted according to standard laboratory procedures.

Figure 5: Polypropylene soilbags provide three-dimensional confinement of soils.

Environmental and Economic Implications

Using waste materials in pavement construction provides environmental benefits by reducing landfill waste, cutting open burning emissions, lowering reliance on cement and lime, and promoting a circular economy. Economically, it can decrease material costs, reduce pavement thickness, and lower long-term maintenance expenses, though comprehensive life-cycle assessments are still limited.

Research Gaps and Future Research Needs

Despite the strong international evidence demonstrating improved UCS, CBR, compaction behavior, and reduced swelling, there remains limited experimental validation under Tanzanian soil types and climatic conditions. Therefore, localized laboratory investigations and field-scale trials are necessary to establish performance benchmarks and develop standardized mix design guidelines for rural road applications in Tanzania. Future researches should integrate lab testing, pilot projects, environmental monitoring, and life-cycle cost analysis

Summary of Reviewed Literature Findings

It has been ascertained through several studies that synthetic nonwoven waste materials (NWM) made of Polypropylene (PP) or Polyester (PET) fibres can be used to improve properties of weak soil in road construction.

The above reviewed studies show great potential of synthetic nonwoven waste materials such as nonwoven packaging bags waste, textile wastes, hospital/ hygiene wastes (nonwoven gloves, surgical gowns and face masks) (Ponnusamy et al., 2024) for improving properties of clay soil in Tanzania where there is challenges of clay soil (Mhando & Kamlenga, 2025) and there is availability of synthetic nonwoven wastes. The materials used by reviewed studies such as plastic bags, polypropylene materials, waste clothes/textiles and disposable face masks share similar polymeric compositions with nonwoven geotextiles (PP and PET) (Sumo, 2024; Iravanian & Ali, 2020). However, some studies used industrial nonwoven geotextiles in soil stabilization (Dienta

& Bağriaçik, 2024) which are more expensive compared to synthetic nonwoven waste materials. Therefore, due to this potential identified, there is a need for further investigation the effectiveness of NWM in improving clay soil for rural roads construction in Tanzania through small fibres, powders and confinement method/soil bags packages. Figure 6 shows flow diagram of the potential of NWM for soil improvement.

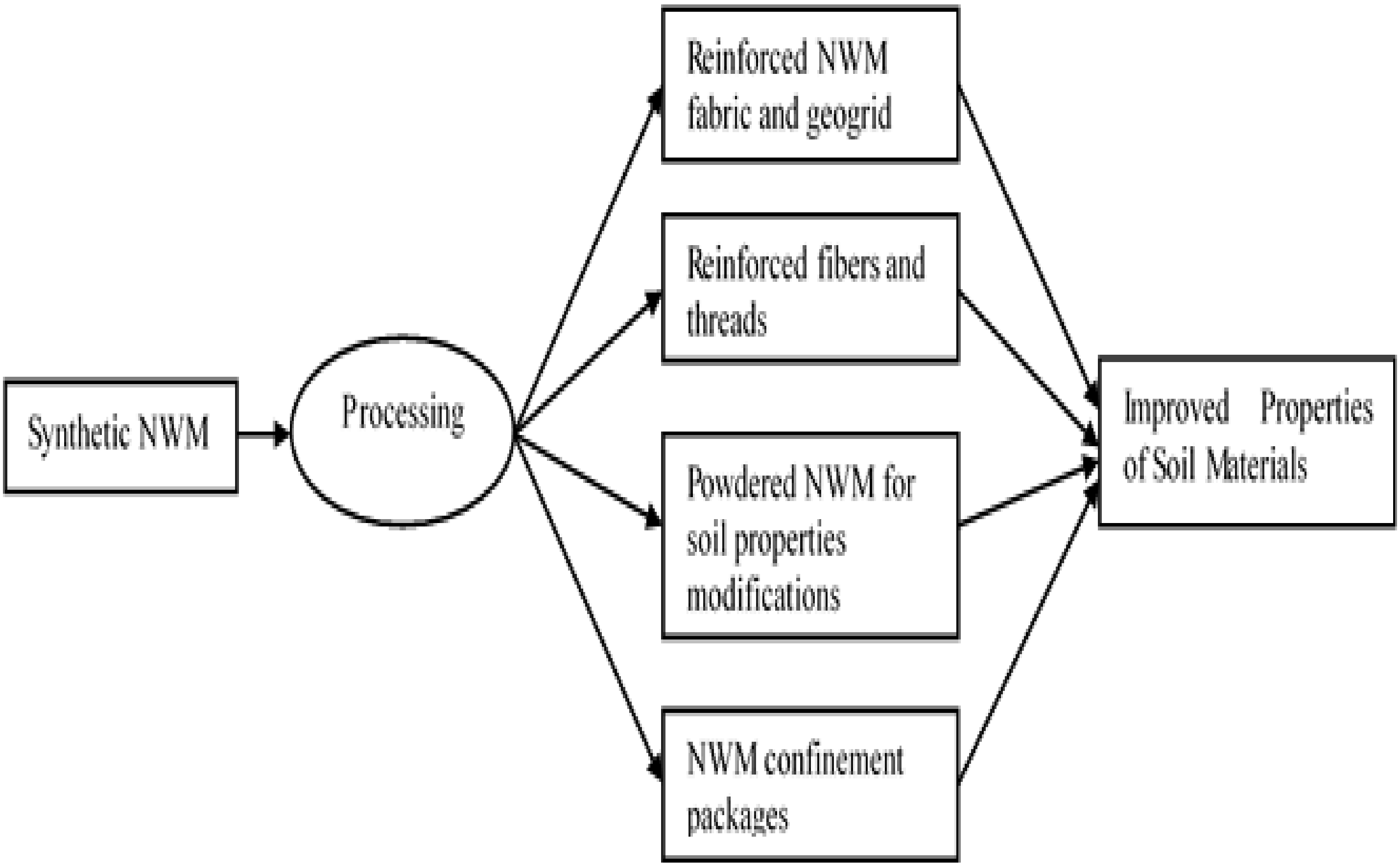

Figure 6: Summary Flowchart of the Review on the potential of Synthetic NWM for Improving properties Clay Soil for Roads Construction

METHODOLOGY

Systematic Literature Review Design

This study employed a systematic literature review (SLR) to evaluate the effectiveness of synthetic nonwoven waste materials (NWM) in improving the engineering properties of clay soils for rural road construction in Tanzania. The SLR approach ensured transparency, reproducibility, reduced selection bias, and structured synthesis of engineering data. The review followed five stages: defining research objectives, identifying relevant literature, screening and eligibility assessment, data extraction, and comparative technical analysis.

Review Objectives and Research Questions

The review addressed five key questions: (i) types of synthetic nonwoven materials used in soil stabilization; (ii) their effects on clay soil properties; (iii) optimal inclusion rates and processing techniques; (iv) implications for rural road construction; and (v) research gaps under Tanzanian soil and climatic conditions.

Literature Search Strategy

A comprehensive search was conducted across Scopus, Web of Science, ScienceDirect, Google Scholar, ResearchGate, and Institutional repositories for studies published between 2003 and 2025. Boolean combinations of keywords such as “synthetic nonwoven waste materials,” “polypropylene fibre soil stabilization,” “nonwoven geotextile reinforcement,” “waste plastic soil improvement,” “disposable face masks," "clay soil reinforcement," "expansive soil stabilization," "CBR improvement," and "UCS polypropylene" were used to retrieve relevant studies.

Inclusion and Exclusion Criteria

Studies were included if they were peer-reviewed and investigated synthetic nonwoven materials (e.g., polypropylene, polyester, plastic bags, face masks, textile waste) for stabilization of clay or weak subgrade soils and reported quantitative geotechnical parameters such as Maximum Dry Density (MDD), Optimum Moisture Content (OMC), Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), or swelling characteristics.

Studies focusing solely on concrete or asphalt, using only natural fibres, lacking quantitative results, or unavailable in full text were excluded.

Study Selection Procedure (PRISMA Framework)

The initial database search identified 54 records. After duplicate removal and title abstract screening, 28 articles remained. Following full-text eligibility assessment using predefined inclusion criteria, 15 experimental studies were retained for detailed technical synthesis. The review selection process followed the PRISMA 2020 guidelines (Page et al., 2021). These 15 studies include: Ahmed (2020), Upreti et al. (2018), Tiwari & Tiwari (2016), Bamrele et al. (2019), Wagare et al. (2021), Guzman & Payano (2023), Eshghi et al. (2025), Chandan & Sharma (2023), Ponnusamy et al. (2024), Shobana et al. (2021), Iravanian & Ali (2020), Xu et al. (2024), Ogundare et al. (2018), Dutta et al. (2009), and Barzoki et al. (2024). Figure 7 illustrates the identification, screening, eligibility, and inclusion stages.

Data Extraction and Comparative Technical Synthesis

A structured matrix was used to extract data on material type, fibre geometry, inclusion percentage, soil classification, laboratory tests, compaction characteristics (MDD and OMC), strength parameters (UCS and CBR), swelling behavior, and reinforcement mechanisms. Data were comparatively analyzed to identify performance trends, optimal dosage ranges, and mechanisms of soil improvement. Percentage improvements relative to untreated soils were calculated where possible.

Engineering Performance Indicators

The review focused on compaction characteristics (MDD and OMC), strength parameters (UCS and CBR), and volume stability indicators (swell index, swell pressure, shrinkage), as these directly influence subgrade performance and pavement design in rural road systems.

Analytical Framework and Contextualization

Findings were interpreted using three reinforcement mechanisms: tensile fibre mobilization, frictional interlocking, and confinement/stress redistribution. Results were further evaluated in the Tanzanian context, considering expansive black cotton soils (CL–CH; A-6/A-7), tropical wet–dry cycles, budget constraints, and limited recycling infrastructure.

Limitations and Future Validation Needs

Variations in soil types, laboratory procedures, and fibre preparation methods limited direct comparability among studies, and long-term field data remain scarce. Future research should include laboratory testing of Tanzanian expansive soils with 0.2–1.5% NWM inclusion, followed by pilot rural road trials and life-cycle cost and environmental assessments.

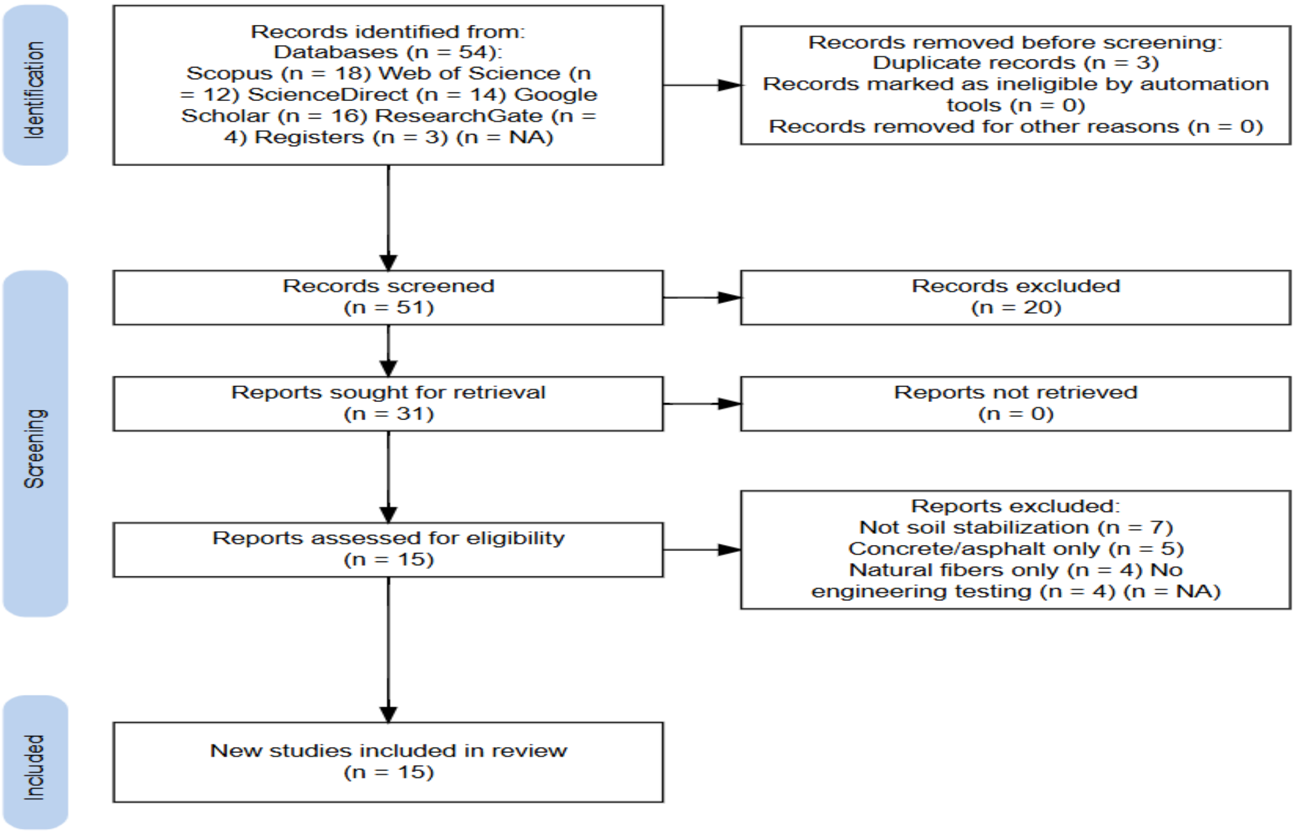

Figure 7. PRISMA 2020 based flow diagram illustrating methodology adopted to review studies investigating synthetic nonwoven waste materials (NWM) for clay soil stabilization

Technical Findings on Synthetic Nonwoven Waste Materials (NWM)

The reviewed literature demonstrates consistent and substantial geotechnical improvements in clay and expansive soils reinforced with synthetic nonwoven waste materials (NWM), primarily composed of polypropylene (PP) and polyester (PL/PET) polymers. Across 15 studies, the inclusion of shredded fibres, textile wastes, plastic bag strips, disposable face mask fibres, recycled carpet waste, and nonwoven geotextile systems showed measurable enhancement of strength, bearing capacity, and volumetric stability of weak soils used in road construction. Overall, the findings consistently demonstrate that synthetic NWM significantly enhance key engineering properties of clay soils when incorporated at relatively low dosages, typically ranging between 0.2% and 1.5% by dry weight of soil, with optimum fibre lengths generally between 10 mm and 40 mm (Upreti et al., 2018; Barzoki et al., 2024; Ahmed, 2020; Shobana et al., 2021). Strength improvement is primarily attributed to fibre–soil interlocking, tensile resistance mobilization, crack-bridging mechanisms, and three-dimensional confinement effects.

Unconfined Compressive Strength (UCS) Performance

Most studies report substantial gains in Unconfined Compressive Strength (UCS) were widely reported. The addition of 1% polypropylene fibres (12 mm length) increased UCS from 15.19 N/cm² to 19.21 N/cm² due to fibre–soil interlocking and tensile resistance mobilization (Upreti et al., 2018). Similarly, recycled carpet waste at 1% content improved UCS from 174.7 kPa to 216.7 kPa, despite a slight reduction in maximum dry density (Eshghi et al., 2025; Mirzababaei et al., 2013). Shredded face masks incorporated at 1% by weight enhanced UCS by up to 64% after 28 days of curing, indicating substantial crack-bridging and reinforcement effects (Chandan & Sharma, 2023). Polypropylene soilbags filled with excavated clay exerted under vertical loading at a rate of 1 kN/s achieved a maximum compressive strength up to 733 kPa before failure, outperforming even some lime-stabilized soils, and demonstrating improved stiffness and deformation control (Xu et al., 2024). These findings confirm that synthetic NWM act as discrete tensile inclusions that restrict shear plane development and enhance overall soil ductility.

California Bearing Ratio (CBR) Enhancement

California Bearing Ratio (CBR) improvements were equally significant and particularly relevant for rural road applications. Recycled polyester textiles increased CBR from 18.1% to 32.4%, effectively upgrading poorly graded sand from subbase to base material classification (Guzman & Payano, 2023). Shredded face masks increased CBR from 1.96% to 6.72% (Chandan & Sharma, 2023), while plastic shopping bag fibres at an optimum 0.3% inclusion increased CBR from 7.05% to 9.0% (Ahmed, 2020; Iravanian & Ali, 2020). Synthetic waste cloth added at 1% content improved soaked CBR values compared to untreated soil, demonstrating the superior tensile properties of synthetic fibres relative to cotton fibres (Bamrele et al., 2019). Bitumen-coated waste cotton fibres further increased CBR by approximately 35.7%, suggesting potential pavement thickness reduction (Wagare et al., 2021). Additionally, nonwoven geotextiles placed at H/4 depth from the base significantly enhanced CBR values of lateritic and clay soils, indicating that strategic placement improves load distribution efficiency (Ogundare et al., 2018). These results highlight the capacity of synthetic NWM to enhance subgrade load-bearing performance and reduce structural pavement requirements.

Compaction Characteristics (MDD and OMC)

With respect to compaction characteristics, most studies reported a slight decrease in Maximum Dry Density (MDD) and a corresponding increase in Optimum Moisture Content (OMC) due to the lower specific gravity and hydrophobic nature of polypropylene and polyester fibres. For instance, disposable face mask fibres reduced MDD from 16.8 kN/m³ to 16.6 kN/m³ while increasing OMC from 18% to 19% (Barzoki et al., 2024). Recycled carpet waste similarly reduced dry density but improved strength due to reinforcement effects (Eshghi et al., 2025). However, some investigations observed moderate increases in MDD attributed to improved particle interlocking and compaction efficiency, such as polypropylene fibre reinforcement where MDD increased from 1.64 g/cm³ to 1.70 g/cm³ (Upreti et al., 2018), and synthetic waste cloth where MDD increased from 1.73 g/cm³ to 1.76 g/cm³ (Bamrele et al., 2019). These variations indicate that compaction response depends on fibre geometry, distribution, and soil mineralogy.

Plasticity and Swelling Behavior

Polypropylene fibre inclusion reduced liquid limit and plastic limit (Tiwari & Tiwari, 2016), and face mask–biopolymer blends significantly reduced free swell index and swell pressure (Ponnusamy et al., 2024). In terms of plasticity and swelling behavior, synthetic NWM demonstrated the ability to reduce shrink–swell tendencies, which is critical for expansive clay soils prevalent in Tanzania. The addition of 0.5% polypropylene fibres reduced the liquid limit by 18.18% and plastic limit by 12%, while also decreasing shrinkage limit and swelling potential (Tiwari & Tiwari, 2016). Furthermore, the combination of 0.5% shredded face masks with biopolymers significantly reduced free swell index from 87% to 21% and swell pressure from 162 kPa to 91 kPa (Ponnusamy et al., 2024). Such reductions are essential for minimizing seasonal pavement distress and improving long-term durability. These findings demonstrate that synthetic NWM can mitigate shrink–swell behavior, a critical challenge in expansive clay soils prevalent in Tanzania.

Confinement and Geotextile-Based Applications

Beyond random fibre reinforcement, confinement techniques using nonwoven polypropylene soilbags and geotextile layers showed promising structural benefits. Soilbags arranged in layered configurations enhanced compressive strength, stiffness, drainage performance, and pore pressure dissipation under loading (Xu et al., 2024). Similarly, nonwoven geotextile sheets significantly increased bearing capacity and reduced settlement in weak soils (Ogundare et al., 2018; Dienta & Bağriaçik, 2024). These confinement systems simulate practical field applications and provide three-dimensional reinforcement, improving stress redistribution within subgrades and embankment constructions.

Integrated Technical Interpretation and Reinforcement Mechanisms

The document review conducted indicates that synthetic nonwoven waste materials function through three primary stabilization mechanisms which are tensile reinforcement effect on which fibres mobilize tensile resistance and restrict crack propagation, frictional interlocking behavior which improved soil matrix bonding and increases shear strength and confinement and stress redistribution on which the use of soilbags and geotextile layers enhance stiffness and reduce deformation.

The optimal fibre dosage range (0.2–1.5%) ensures strength enhancement without excessive reduction in workability or compaction efficiency. Importantly, most improvements were achieved without chemical additives, aligning with low-carbon and circular economy principles.

CONCLUSIONS AND RECOMMENDATIONS

This structured literature review systematically evaluated the geotechnical performance of soils reinforced with synthetic nonwoven waste materials. Guided by the PRISMA 2020 statement, fifteen peer-reviewed studies were critically analyzed to quantify mechanical improvements and assess sustainability implications.

The evidence consistently indicates that low fiber inclusions (approximately 0.2–1.5% by dry soil weight) substantially enhance soil behavior. Reported outcomes include significant increases in unconfined compressive strength (up to 64%), marked improvement in California Bearing Ratio (CBR), reduction in plasticity index, and suppression of swelling in expansive soils. Fiber-reinforced soils also exhibit improved ductility and post-peak load resistance, attributed to tensile bridging, frictional interaction, and crack-arrest mechanisms within the soil matrix. These findings confirm that synthetic nonwoven waste can function as an effective mechanical stabilization agent rather than merely as a filler material.

From a sustainability perspective, this approach enables the valorization of textile and plastic waste streams while reducing reliance on energy-intensive chemical stabilizers. Such integration directly supports circular economy objectives and advances environmentally responsible ground improvement strategies.

Despite robust international evidence, context-specific validation remains limited, particularly for regions with distinct soil mineralogy and climatic conditions. Future research should therefore prioritize experimental validation using locally sourced nonwoven waste materials, durability assessment under cyclic environmental loading, and the development of performance-based design frameworks to facilitate field-scale implementation.

Overall, synthetic nonwoven waste materials demonstrate strong potential to simultaneously enhance geotechnical performance and address waste management challenges, positioning them as a viable component of sustainable infrastructure systems.

Funding Statement

No external financial support, grants, or institutional funding was utilized throughout this manuscript.

ACKNOWLEDGEMENT

We are thankful to the College of Engineering and Technology (CET) of Mbeya University of Science and Technology (MUST) for their valuable guidance, support, and timely feedback during preparation of this manuscript.

Declaration of Conflict of Interest

The authors declare no conflict of interest

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