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Research Directions

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Developing and characterizing a typology of soil fabrics

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Abstract

Synthetic textiles, such as polyester, are resistant to natural degradation and constitute approximately 65% of global circulating textile fibers, posing a significant environmental challenge due to their persistence in ecosystems. The global textile industry is responsible for nearly 10% of total global carbon emissions annually and increasing environmental waste. One emerging solution to the industry's negative environmental impacts is bio-based textile materials that are biodegradable and low-carbon to reduce dependencies on petroleum oil. This paper presents the evolutionary design journey and novel development of earth- and bio-based wearable textiles, coined as *BioMud Fabrics,* which consist entirely of geo- and bio-based materials. The qualitative and quantitative research-by-design methodological toolkit includes material characterization analysis, microstructural analysis using scanning electron microscopy (SEM) and macro-scale structural characterization using tearing tests following ASTM D5587. The developed fabrics were then applied in a series of speculative design demonstrations with fashion design serving as a central case study. This research uniquely combines material science and engineering with exploratory fashion design and architectural practices with the goal of offering radically innovative biomaterials in an effort to shift towards a more circular material paradigm.

Introduction

The textile industry is a major contributor to significant carbon dioxide emissions and environmental pollution and accounts for over 10% of global carbon emissions annually (equivalent to 1.2 billion tonnes of CO_2) (UNFCCC 2018; Leal Filho et al. 2022). With about 60% of textile production allocated to clothing, the fashion sector remains a primary driver of the industry's carbon footprint (Niinimäki et al. 2020) because synthetic fibers, predominantly polyester derived from petroleum oil, constitute over two-thirds of textile fibers (Palacios-Mateo et al. 2021). Beyond emissions, landfilling and incineration dominate textile disposal, with less than 1% of textiles being recycled (Morlet et al. 2017). An emerging environmental solution to respond to the textile industry's environmental crisis involves developing bio-based textiles that are biodegradable, recyclable and resource-efficient. Innovations like fabric made from yeast cultures (Werewool 2022) and recombinant proteins (Tachibana et al. 2021) showcase the potential of such fabric alternatives.

To address this ongoing need, this research develops mix-designs that consist entirely of geo- and bio-based materials, primarily observing an integration of clay-rich raw soil with bio-based, food-grade polysaccharides. The main goal of this research is to examine a range of mix-designs to produce new material landscapes towards circularity.

Earthen materials historically used in wearables and fabric design

Clay-rich subsoils are composed of a range of particle distribution, including sands, silts and fine clay particles (Elert et al. 2022). When processed and then dried, earth materials can easily be broken down back into its original composite form with the addition of water alone. The unique reversible metamorphosis life cycle of clay-rich soils poses a critical intervention for the future of sustainability in design development across disciplines and sectors. Additionally, healthy clay-rich soils, or soils that have beneficial microbes may have positive long-term impacts on human's emotional wellness and psychological, gut well-being (Hirt 2020).

Historically, clay-rich soils have been used to dye and treat fiber-based fabrics as shown in Figure 1. One such technique is Dorozome, a dyeing technique original to Amami Oshima, Japan, where local fabrics are pigmented by soaking the fabric in mud baths or muddy rice fields (Linton 2020). Meanwhile, the process of creating Malian "mud" cloth, or bogolanfini, involves paint-dyeing clay soils onto textiles traditionally done by Bamana women artists who treat the clay paint in processes that can last up to a year before it is ready for use (Barton 2007; Toerien 2003).

Figure 1. From left to right: Several garments line drying after being dyed in a mud-field (Image credit: Fukamizu, 2022); resident dyeing Osima tsumugi yarn in mud fields (Image credit: Visvim, 2022); storage of mud for painting and dyeing purposes (Imperato, 2006); mud-painting process on treated cloth-based fabric (Image Credit: Imperato, 2006).

However, contemporary fashion design largely overlooks the use of clay-rich soils likely due to the material's initial functional constraints concerning flexibility, weight, volume and strength capacities. Clay-rich soils, therefore, require further experimentation and demonstration of their capacity within textile design for expanded wearable and architectural imagination. To address this need, this study pioneers the integration of clay-rich soils into fabrics and wearables. It characterizes local soils, sculpts garments, devises food-grade polysaccharides-infused soil textile mixtures and develops different design typologies through rigid garments and flexible soil fabrics which are laser-cut, embroidered and machine-sewn.

Research-by-design methodological toolkit

This study uses a research-by-design methodological approach, as shown in Figure 2, with a procedural toolkit initiated by material selections, material composite processing and applied design typologies: rigid garments and flexible fabrics.

Flexible soil fabrics also underwent a material characterization and diagnostics analysis. The chosen materials for experimentation included clay-rich soil sourced from Goshen, New York which was characterized by an ASTM standard sedimentation test and then pre-treated using a pre-pottery technique called Terra Sigillata. Biopolymers utilized in the experiment such as cornstarch, glycerin, alginate, cellulose, gelatin, agar were all sourced from Millipore Sigma. Reinforcing fibers included wheat straw, paper waster and fluids included water and vinegar.

The process of creating material compositions for soil fabrics involved manually hand mixing dry ingredients into uniform distribution (which generally took about 2–3 minutes of continuous mixing or when all dry ingredients were visibly combined) while following volume proportional amounts found in the mix-design representations Table 1.

Reinforcing fibers and fluids were then mixed in for another 2 minutes or until all ingredients were visibly combined. The biopolymer mix designs were cooked at 162 °C to 176 °C for 10 minutes using a 1500 W electric hot plate and manually stirred during the entire duration in order to prevent burning before being shaped into fabric sheets using 27 × 40 cm silicone mats as seen in Figure 3. These fabrics were cured in an open-air, room temperature (20 °C) space for 5–7 days. Exact humidity levels were not measured during the time of curing but should be in future investigations to better understand the relationship between humidity and curing impact. For rigid garments, a mold was created by plastering a human torso as seen in Figure 3 where soil mix-designs were shaped over and then cured for four days.

Material characterization and diagnostics: Flexible fabrics

The flexible soil fabric mix-designs underwent both qualitative and quantitative material characterizations.

Qualitative analysis: Texture and motion

The qualitative analysis included flexibility, textural and tearing characteristics, as shown in Figure 4. The fabrics' flexibility was determined by bending the fabric horizontally and assessing its range of motion, scored between 1 (non-flexible) and 2 (flexible). Tearing test scores ranged from 1 (easily tearable) to 4 (non-tearable). Textural qualities like stickiness, thickness and opaqueness were visually examined.

Quantitative analysis: Tearing strength and electron microscopy

The quantitative analysis included a microstructural analysis using electron microscopy and a strength tearing characterization test employed by a standard trapezoid procedure using a CRE tensile testing machine (ASTM D5587). Sample specimens of the soil fabrics were cut to standard (150 mm × 75 mm) and clamped onto the machine with 50 mm × 75 mm hydraulic pneumatic clamping systems. The distance between the clamps at the start of the test is at 25 ± 1 mm (1 ± 0.05 in.) and the testing speed is 300 ± 10 mm (12 ± 0.5 in./min).

Shredded agricultural bast fibers were introduced for consistent reinforcement. Flexible soil fabrics with fiber reinforcement were shown to exhibit coverage magnifications from 150X to 500X nano millimeters, revealing evenly distributed circle-shaped bulbs in the matrix, likely due to added gelatin and alginate biopolymers, as shown in Figure 5a, 5b. These fibers formed vertical columns across the matrix gaps, binding and reinforcing the material, potentially enhancing interconnection and strength, as shown in Figure 5c, 5d. Observations of flexible soil fabrics without any fiber reinforcement spanned magnifications from 150X to 5.00K X, revealing a dense matrix with varied vertical crystallization forms, as shown in Figure 5e, 5f. Crystallization forms, seen in Figure 5g, 5h, occurred sporadically throughout, displaying diverse shapes and sizes potentially indicating variable bond cohesion and matrix inconsistency.

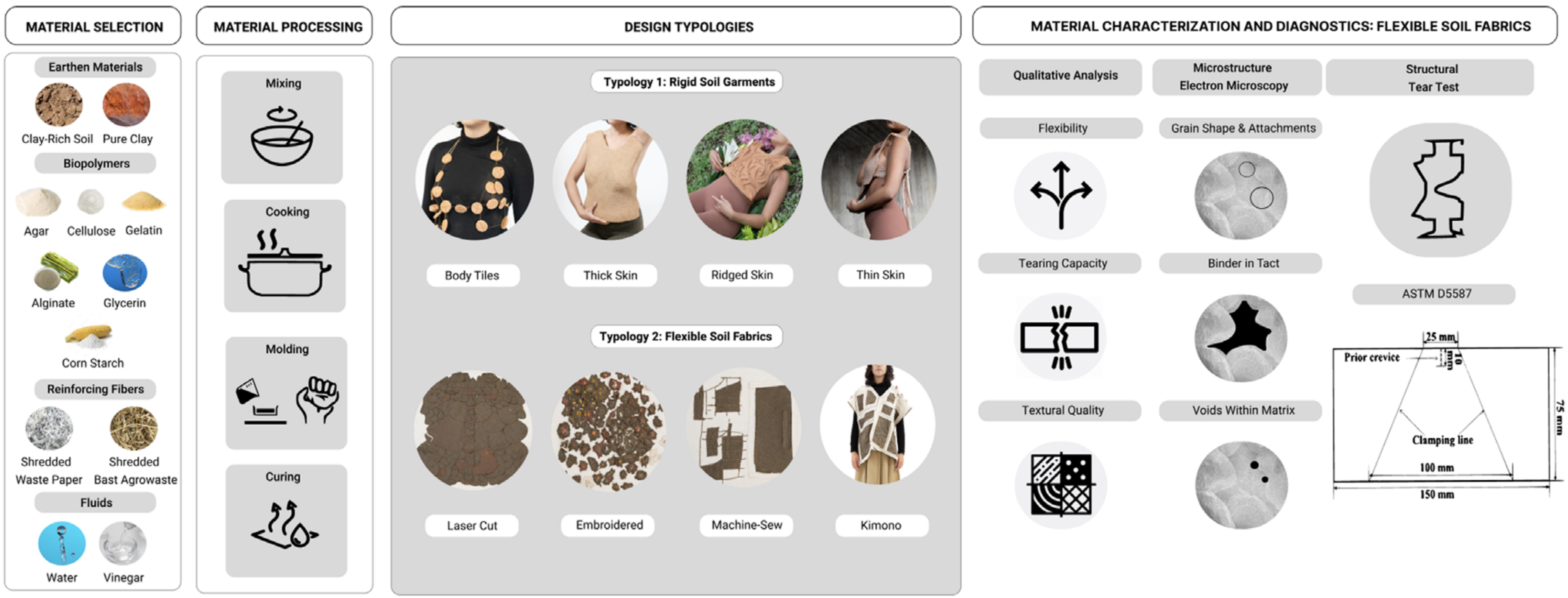

Figure 2. Research-by-design methodological toolkit.

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Table 1. Mix-design volume proportions of flexible soil fabric

Mix-design representation	Soil to biopolymer	Reinforcing fibers to soil/biopolymer
W/ Fiber	28%	25%
W/O Fiber	28%	0%

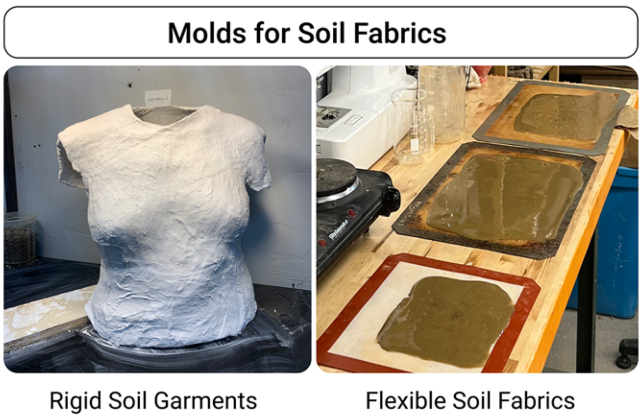

Figure 3. Molds used to create soil fabrics.

For the tearing tests, ASTM D5587 standard test results exhibited high variability in force distribution over time for fabrics with and without fiber reinforcement, suggesting low non-uniform strength. However, fabric with fibers exhibited significantly higher peak loads (4.0N at around 12.4 mm crosshead point) before tearing compared to fiber-less samples (2.8N at around 14.2 mm). Therefore, incorporating fibers into flexible soil fabric mix-design recipes can be a crucial additive to improve strength performance of the material but requires additional experimentation in order to identify its optimal ratios. Other studies have also shown that the tensile strength of starch-based bioplastic materials tends to decrease as the glycerol content increases (Abe et al. 2021). For soil fabrics, a starch-based bioplastic fabric, it might be important to explore alternative plasticizing materials that can enhance flexibility without compromising tensile strength but further research is needed to identify such materials.

Design typology one: Rigid soil garments

Four rigid soil garment typologies were developed: 'Body Tiles', 'Thick Skin', 'Ridged Skins', 'Thin Skin'. The "Body Tiles" mix-design, shown in Figure 6a, was transformed into small circular tiles (30 mm in diameter) marked with holes to allow a weaving pattern to be constructed between tiles and to cover the breast area. These body tiles were lightweight and versatile but functioned more as a body accessory than a full torso wearable. This conclusion prompted further exploration of alternative soil garment construction methods. The "Thick Skin" mix-design, shown in Figure 6b, incorporated one reinforcing fiber within the final soil composition in an effort to build a more cohesive but structurally sound torso garment. However, this method required a significant amount of material to build the garment's structure, which weighed on average 3 kg and measured 30–34 cm wide, 40 cm tall and 1.5 cm thick. The volume of material needed to construct the garment also posed functional challenges to the wearability of the piece. Thus, research continued to pursue lighter but stronger construction method alternatives. "Ridged Skins", utilized material to form vertical crests across the garment's face in an effort to enhance the structural integrity of the garment, shown in Figure 5c. These garments weighed on average 1.7 kg and measured 34 cm wide, 40 cm tall and 1.5 cm thick. Despite improvements in the structural integrity of the garment, hands were still needed to wear the garment due to its weight. Finally, the "Thin Skin" mix-design (Figure 6d) utilized two reinforcing fibers within its soil composition which reduced the need for added structural reinforcement and material. The outcome from this material evolution and construction method resulted in an ultrathin soil garment (about 0.5 cm thick) that weighed on average 1 kg. The "Thin Skin" garments were light enough to incorporate shoulder strap mechanisms. Some straps were made of the soil material, while others were cotton sleeves that were pasted with "mud glue" onto the thin skin garment's shoulders.

Design typology two: Flexible soil fabrics

Four flexible soil fabric typologies were developed: 'Machine-Sewed Soil Fabric', 'Embroidered Soil Fabric', 'Laser-Cut Soil Fabric' and 'Kimono Soil Fabric'. The 'Machine-Sewed Soil Fabric' utilizes fabric sheets in construction through conventional machine-sewing techniques, as shown in Figure 7c. Direct needle contact on the fabric sheets was shown to occasionally cause tearing and thus required optimized tension and speed. Despite efforts to control the amount of ripping, the process remained challenging when it came to sewing larger-scale patterns. Excess flexible soil fabric scraps were gathered and repurposed for 'Embroidered Soil Fabric', as shown in Figure 7b, in an effort to reuse all developed material. Meticulously layered, the embroidery process enhanced the flexible soil fabric's material stability and strength. However, the labor-intensive embroidery process extended fabrication time for wearable soil fabric garments made from embroidery and limited the size of the final forms. The flexible soil fabric sheets were also laser-cut into organic shapes inspired by Southeast Asian amphibious creatures to create 'Laser-Cut Soil Fabric', as shown in Figure 7a. The individually cut pieces were sewn onto canvas fabric and showcased improved durability, reduced weight, enhanced flexibility and more streamlined fabrication processes resulting in the most successful and wearable demonstration of BioMud Fabric. Finally, 'Kimono Soil Fabric' was created, achieving complete torso coverage. This showcased the material's use in fashion applications, in its truest sense and employed all three learned fabrication techniques into its final design. The Kimono with the BioMud Fabric highlighted the material's flexibility and ability to adapt to the dynamism of human movement, as shown in Figure 7d.

Discussion and significance

The textile industry's vast use of synthetic materials leads to an environmental crisis, requiring critical developments of fabric materials that are readily available and biodegradable. This study develops a geo- and bio-based fabric of raw clay-soil as depicted in Figure 8. The fabric development was articulated primarily through fashion and architectural design speculations. This biodegradable material emphasizes the rawness of its components and integrates bio-based plastics derived from naturally occurring biopolymers and minimally processed soils to create a flexible fabric that can also be speculated for design beyond those

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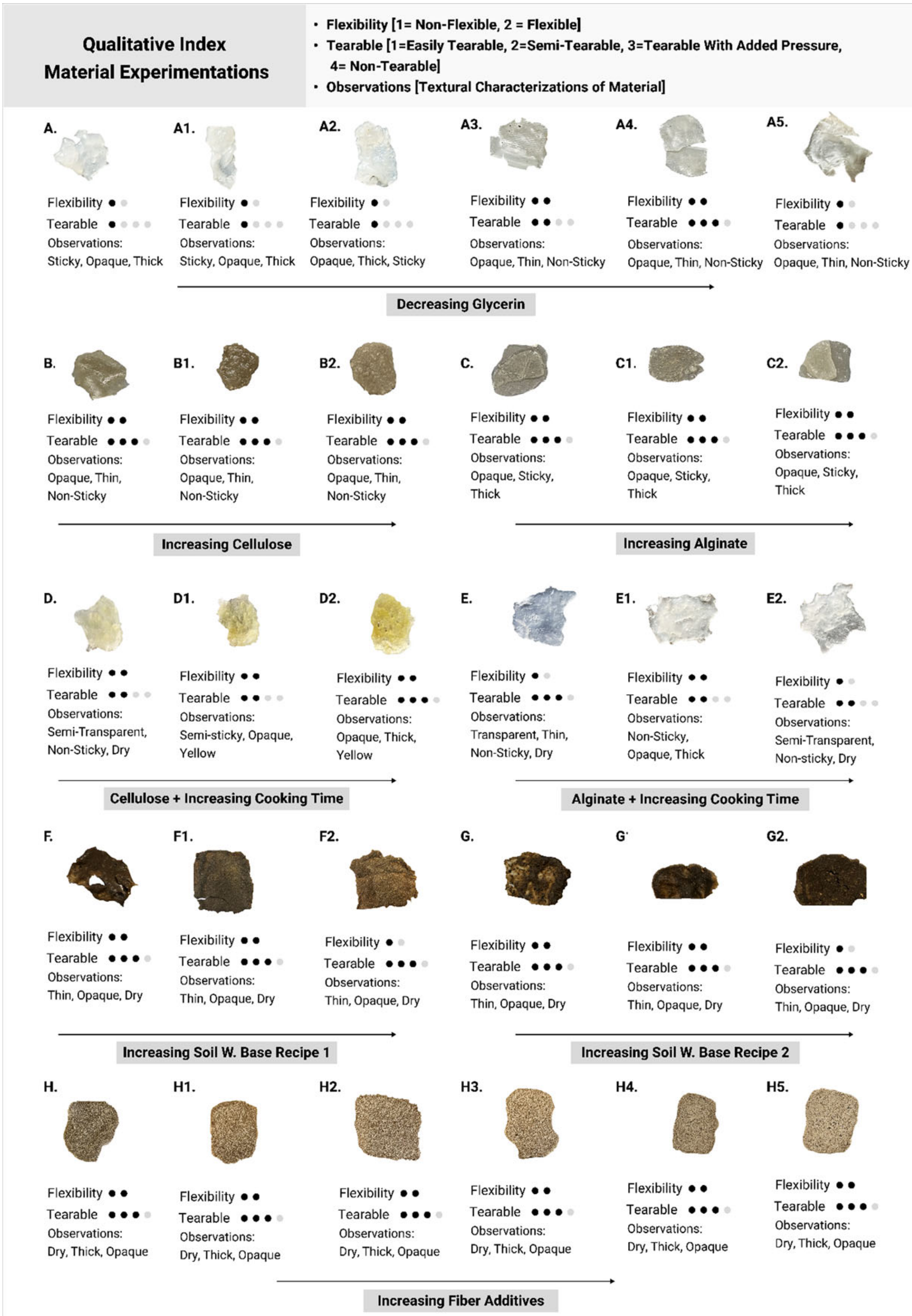

Figure 4. Qualitative index of material experimentations.

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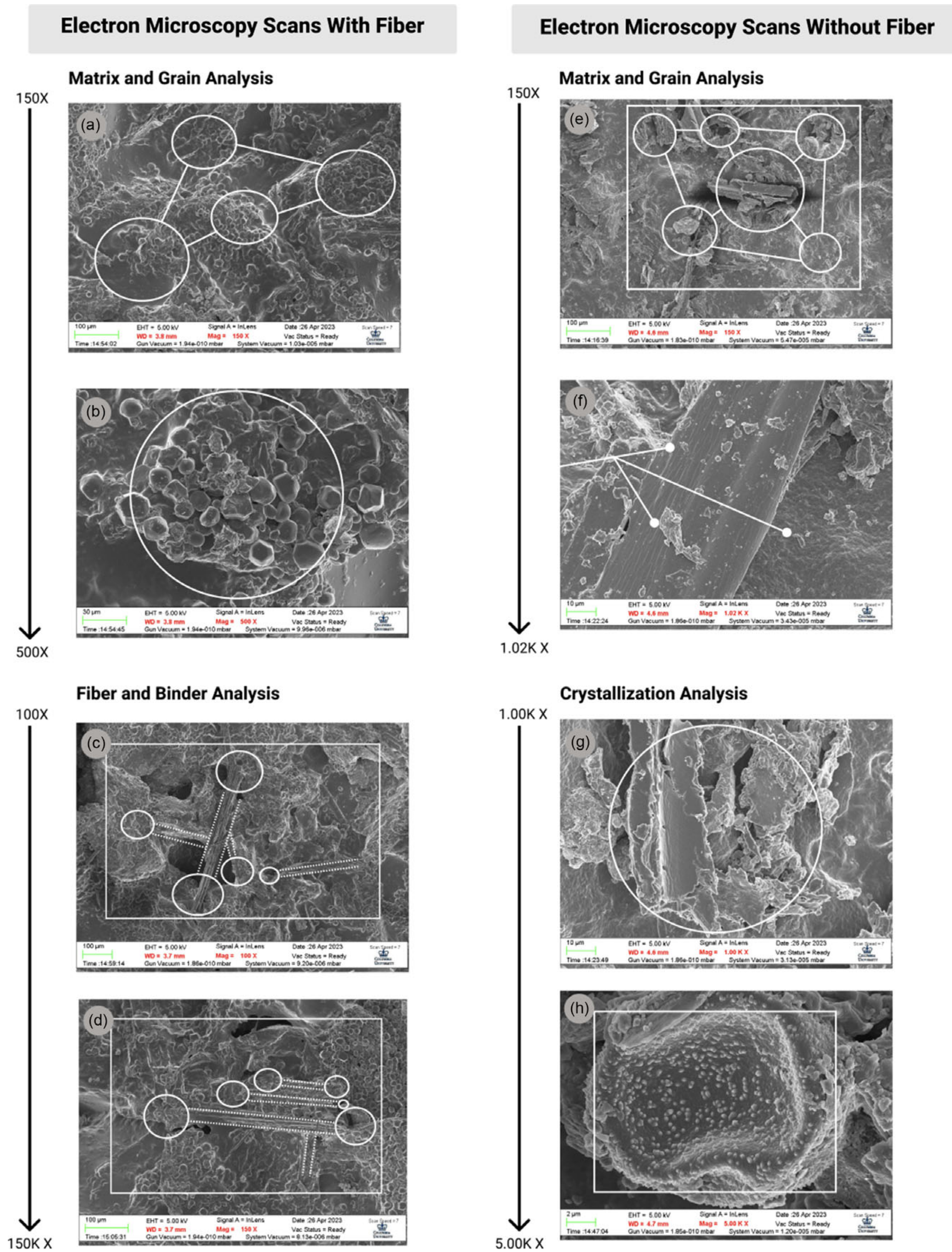

Figure 5. (Left) Electron microscopy scans with fiber reinforcement; (Right) electron microscopy scans without fiber reinforcement.

Figure 6. (a) Body tiles; (b) thick skin; (c) ridged skin; (d) thin skin. Photographer credit: Changbin Kim; Yunha Choi.

Figure 7. BioMud fabric as architectural panels and as a wearable. Photographer credit: Florianne Jacques.

presented in this study, including interiors to food packaging to agriculture. For example, BioMud Fabric might be able to address large-scale nano plastic contamination in agricultural production from plastic mulch films by serving as a compostable film replacement.

The flexible soil fabric strictly uses naturally derived food-grade polysaccharides, as opposed to other bioplastic and petroleum-based additives that use bio-synthesized materials. These materials must undergo a biodegradation process within optimized composting and recycling conditions to ensure full biodegradation of materials, which may pose challenges in post-usage processing, especially for smaller-scale facilities of textile production. Additionally, though the use of food-grade ingredients lowers carbon dioxide gas emissions through reduced fossil fuel use, an increase of farming cultivation to maintain sustainable textile production through deforestation and grassland conversion may also impact net greenhouse gas emissions. Other proximal environmental concerns related to this production process arise

Figure 8. Flexible soil fabrics with and without fiber aggregates. Photographer credit: Emine Taha.

such as threatened biodiversity through increased crop monoculture farming (Rujnić-Sokele & Pilipović 2017). For both developed soil typologies, the main composite of raw soil, which have minimally processed plastic materials that exhibit low-carbon features (Ben-Alon et al. 2019; Ben-Alon et al. 2021), uniquely creates a local supply chain of the material and with a methodology that can draw upon locally sourced raw materials in any geographic, topographic region that has access to healthy soil. From clay-rich soils from Colorado to sandy soils in sub-Saharan Africa, the different composite properties of soils will promote different textile opportunities of circular supply chains, texture, color and microbial speculations. This open-source access point for material development and textile application has the potential to address proximal social concerns associated with the textile industry such as labor concerns across the global supply chain and carbon-heavy resource extraction practices. It is important to note that extraction for soil resources for textile outcomes would pose long-term ecological concerns related to natural resource mining but might be mediated by identifying sustainable waste streams of soil that can be utilized within a circular supply chain. Future investigations should continue to assess the entire life cycle of soil textile processes in different contexts including that of soil organisms. Additionally, future investigations might look at the practical and economic viability of the soil textile life cycle processes in order to understand their potential market impact.

The raw soil within the fabric contains living bacteria that are beneficial for human health. Research shows that exposure to friendly soil microbes can help to improve mood regulation as well as improve a human's immune system (Ottoman et al. 2019). Future investigations might specifically look at the microbial impact on wearers of soil garments. Soils offer cultural, communal and aesthetic benefits, contributing to a collective and location-specific land upkeep that can enhance elements beneficial to both the physical and mental well-being of individuals (McBratney et al. 2014) and play a vital role in creating aesthetically pleasing environments for communities to reside in (Brevik et al. 2020) – or wear.

Finally, a differentiating social impact is offered by soil fabric typologies. These typologies draw upon the deep seeded wisdom imbued within the Earth to inform a contemporary design relationship with the natural environment by bringing soils close to the human form. Reconnecting with the human form through soil wearability encourages a profound and attentive recall of our connection to the soil. This fosters an increased awareness of the Earth's resources, prompting us to consider better management of these resources and, consequently, our relationships with one another.

Conclusion

This paper aims to catalyze soil-based fabric possibilities to curb the environmental concerns related to the global textile industry in both fashion and architectural design. The presented research hopes to positively impact various facets of human life alongside shifting the current material paradigm towards a more circular and environmentally conscious state. Future research should investigate the strength capacities and life-cycle analysis of soil-based fabrics as well as further investigate human health outcomes when in contact with clay-based, mineral-rich subsoil, building upon existing evidence that exposure to friendly soil bacteria has positive effects on physical and mental well-being.

Data availability statement. The data that support the findings of this study are available from Columbia University. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the authors with the permission of Columbia University.

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Author contributions. Penmai Chongtoua and Lola Ben-Alon conceived and designed the study; participated in validation, data curation, formal analysis and writing – review, editing and proofreading. Lola Ben-Alon provided additional project administration and supervision efforts.

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