AUXETIC GEOMETRIES IN EARTH–FIBER 3D PRINTING:

From Bodily Landscapes to Architectural Terrains

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ABSTRACT
Auxetic geometries characteristically have a negative Poisson ratio which is defined by a geometric sequence that expands laterally when pulled in the direction perpendicular to a pulling force. This geometric characteristic affords unique properties, including energy absorption and the ability to adapt to bending forces. Auxetic geometries have, therefore, been positioned as strategic design solutions for high performability applications, including crash protection and urban infrastructure. In responsive boundary spaces, where the need for rapidly iterative and flexible material design is necessary in face of climate change and environmental cataclysm urgencies, auxetic geometries offer a compelling future for architectural natural material contemporaries that also allow for biodegradability and nutrition to the land at the end of life. This paper presents explorations of 3D printed auxetic-inspired geometries with natural earth- and fiber-based materials for architectural textiles. The methodology includes three steps: (1) a review of auxetic geometric behaviors, (2) 3D printed tests of two-dimensional patches using two earth-fiber mix-designs: agar and locust bean-gum based optimized with specific auxetic geometric sequences (3) auxetic-inspired earth-fiber geometries 3D printed directly onto the shape of a terrain, 3D scanned from a bodily torso "landscape" for continued speculation towards applications in between urban and wearable applications.

1. INTRODUCTION

Auxetic geometries, derived from the Greek word auxetikos meaning “that which tends to increase”, characteristically have a negative Poisson ratio, which is defined by a geometric sequence that expands laterally (in width or thickness) when pulled in the direction perpendicular to a pulling force.

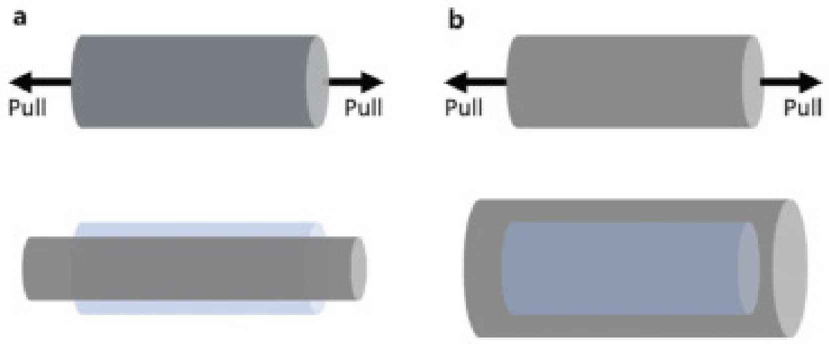


Figure 1:
**Visualizing the difference between non-auxetic mechanical Properties (a) vs. auxetic mechanical properties (b).
Source: Mechanics of auxetic materials.**

Auxetic geometries can be further broken down according to their deformation mechanisms and/or the structural tendencies that enable their auxetic behavior into classifications of re-entrant structures; chiral structures; fibril/nodule structures; miura-folded structures; rotating unit structures; helical yarn structure; buckling-induced structures; and crumpled structures as seen in Figure 2 (Cho et.al, 2019).

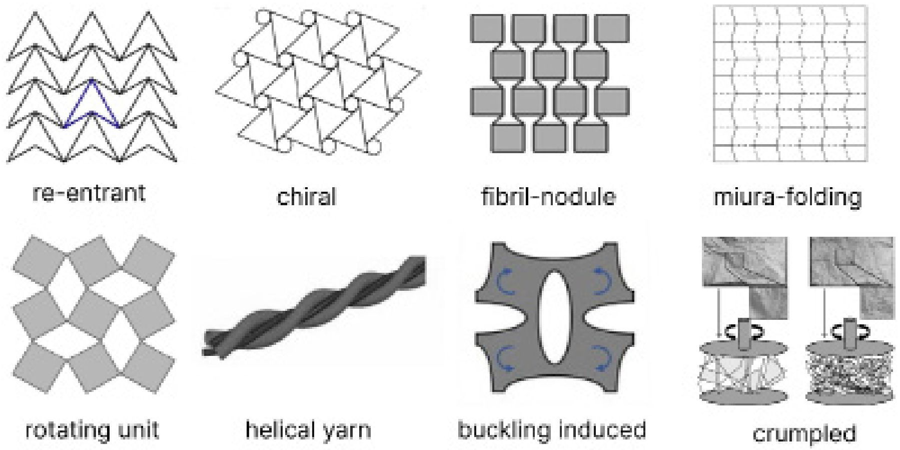


Figure 2:
Classifications of auxetic geometries

These geometric characteristics afford unique features, including energy absorption, resistance to fracture, the ability to adapt to a bending force and resistance to failure due to shear load which has placed auxetic geometries strategically in application within high material performance contexts, including but not limited to crash protection, body armor, and sports equipment (Papadopoulou et.al, 2017). Specifically, the re-entrant auxetic geometry, often described as an inwardly "notched" or "bowtie" shape, is one of the most common auxetics and will serve as the central auxetic geometric focus for this study. These structures consist of unit cells with angled struts or ribs that collapse inward upon stretching, causing the material to exhibit auxetic behavior, with geometric properties that enhance shear flexibility (Lakes, 1987).

In responsive boundary spaces, where the need for rapidly iterative and flexible material and design solutions is necessary in the face of climate change and environmental infrastructural urgencies, auxetic geometries offers an important solution to flexible and resilient geometries, offering new possibilities within architectural contemporaries that present more environmentally sensitive material design use cases.

The process of digital fabrication by way of 3D printing has been shown to offer greater geometrical accuracy and production efficiency for architectural and textile contexts but most materials used in 3D printing processes are synthetic polymers, calcined materials, and metals that have critical environmental and carbon-intensive trade-offs when used (Soyeon Park, 2022; Guo Liu, 2021). Natural earth- and bio-based materials, however, are minimally processed and use natural substances that may mitigate carbon intensities by reduced need for thermal and chemical processing (Akemah & Ben-Alon, 2023). Additionally, these materials are often defined as locally available (Carcassi & Ben-Alon, 2024) and often have characteristics of biodegradability, lower embodied energy, and carbon sequestration qualities, especially during their growth phases, thereby reducing the overall carbon footprint of buildings (Pittau et al., 2018) positioning these materials positively in efforts toward decarbonization in urban landscapes.

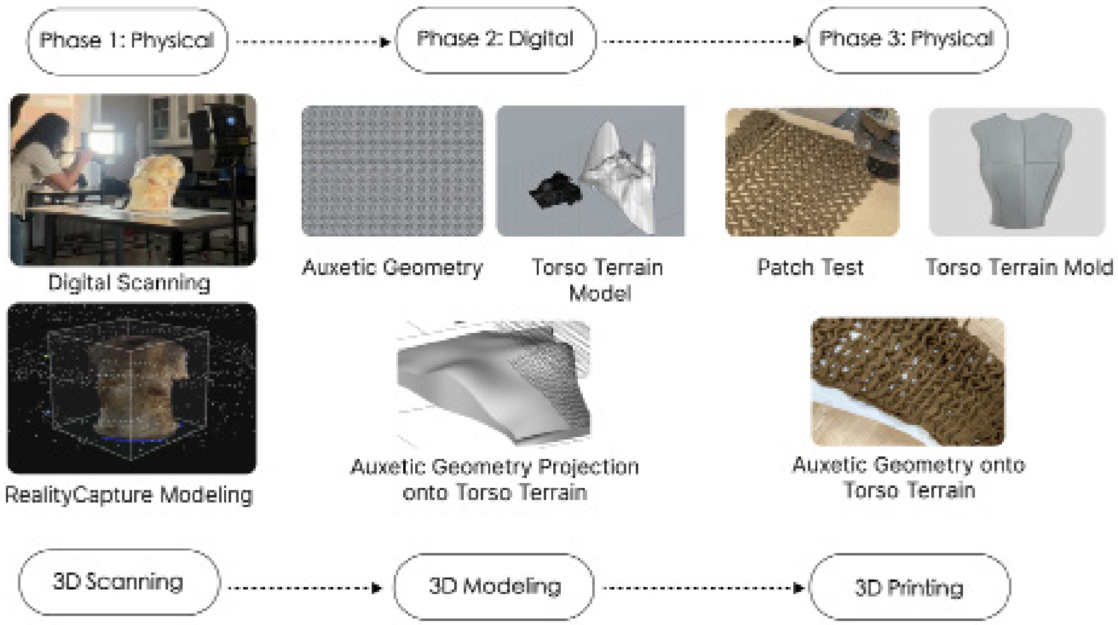
Earth- and bio-based mix designs are made from clay-rich soils as the base paste materials, reinforced with natural fibers, and often stabilized with natural additives to enhance the rheology, strength, and stiffness of the final mixture (Maierdan et. al, 2024). Most recently, the authors have developed a range of textile innovations using earth-fiber mix designs “recipes” for digital 3D printable structures, in which 3D-printed geometries are implemented using non-auxetic geometries within planar dimensions (Te & Ben-Alon, 2023). Auxetic geometries have been explored in textile applications, but predominantly with traditional fiber materials like polyester and polyamide (Steffan et. al, 2017). This study thus aims to expand the lexicon of geo- and bio-based materials for radically sustainable auxetic geometries and applications.

For continued optimization of earth- and bio-based fiber mix-designs gestured toward textile applications for infrastructure landscape terrain, bodily, and architectural contexts, auxetic geometries might provide then, through geometric design itself, an increase of the usability of this earth- and bio-based material, by adapting the capabilities of the material. This paper summarizes an exploration of 3D printed auxetic-inspired geometries with earth-fiber mix designs for textile applications. The methodology includes iterative auxetic geometric design sequences based on test prints of planar patches using two earth-fiber mix-designs – agar base and locust bean-gum based – to a final deliverable of auxetic-inspired earth-fiber geometry 3D printed onto a 3D scanned base in the shape of a torso, reinterpreted as a landscape terrain, for speculation towards future ready-to-wear applications and expanded infrastructure intervention strategies.

2. METHODOLOGY

The methodology focused on three phases, beginning with a physical phase enabled by 3D scanning, to a digital phase enabled by 3D modeling, and finally into the final physical phase stage, enabled by 3D printing, as seen in Figure 3. The first physical phase included 3D scanning translations which focused on using methods of photogrammetry to digitally scan a pre-designed plaster torso previously casted to the scale of a human size of a woman's body. The torso was conceptualized and interpreted as a landscape terrain and functioned as the tool to visualize the earth- and bio-based auxetic geometry's physical interplay with landscape topographies, while also maintaining a connection point to the body for future speculation in ready-to-wear deployment and other potential landscape interrogations and/or interventions.

Figure 3:
The research methodology employed in the presented research.



The digital phase included 3D modeling in three separate processes. The first process included modeling three re-entrant auxetic geometries, each selected and designed to compare optimization pathways between earth-fiber mix designs and auxetic geometries. The second process included transferring the digitally scanned model of the torso into a torso terrain, to create more specific landscape connection points from the bodily context to a topographic landscape potential. The life-size torso model was also simplified during the digital phase by reducing the scanned model's triangle count in RealityCapture to facilitate a transferable 3D-printed mold in RHINO for physical printing processes, which was sliced into sections in order to fit on the printing bed while remaining at life-scale and to enable future speculations for ready-to-wear applications (i.e. printing materials directly onto the body into wearables). Finally, the most 'successful' auxetic geometry was selected and projected onto the torso terrain model, in preparation for the final outcome of printing directly onto the landscape terrain.

The final physical phase also included a 3D printable material design methodology, as seen in Figure 4, which resulted in a comparison between three different auxetic re-entrant geometries planar patches, with each geometric print compared between two different earth-fiber mix-designs used in previous earth- and bio-based textile applications, an agar based (Sittigaroon, 2024) and locust bean gum-based mix-design, to assess how variations in earth-fiber mix designs interact with the presented auxetic geometries.

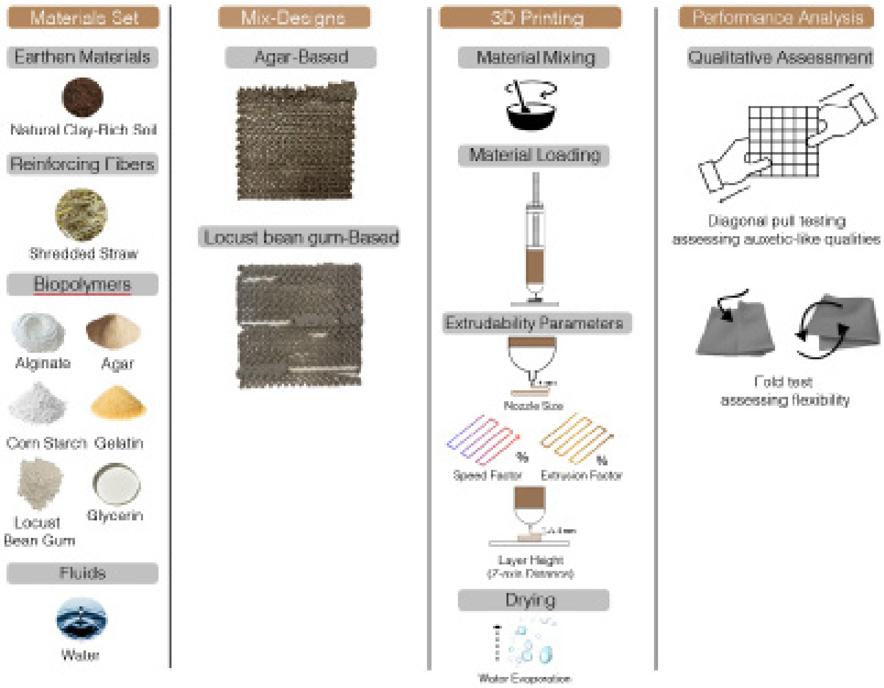


Figure 4:
Material design research apparatus for the 3D printing and planar patch assessment.

As mentioned, mix designs were chosen based on their previously qualitatively assessed potentials for increased flexibility enabled by agar's gelling characteristics (Kalpanin et al, 2924) and locust bean gum's strength (Lv et al, 2019) and contain a precise combination of materials including earthen materials: natural clay-rich soil; reinforcing plant fibers; biopolymers such as alginate, agar, corn starch, locust bean gum, gelatin, and glycerin; and water fluids. After qualitatively assessing the printed auxetic planar patch with varying mix-designs, a final patch was assessed as the most 'successful' if it exhibited both 'very flexible' and 'auxetic-like' parameters. This informed which mix-design and auxetic geometry was optimized for and could proceed forward in 3D printing onto the torso terrain. For the digital 3D printing phase, printing scripts were optimized in Grasshopper, which was especially important when printing the final deliverable to ensure that the printing pathways for variable z-axis heights created by the topographic nature of the torso terrain were being accounted for. The connection point between the digital model and the physical printing process was also enabled by digital model plane alignment but also required some level of manual measuring adjustments during the physical printing process to ensure alignment between the start of the print and its spatial relationship to the physical model. The physical model was adjusted onto the bed in this manner and was printed directly using the selected auxetic geometry and earth- and bio-based mix design.

3. RESULTS

Translating the human torso into a landscape terrain by way of physical to digital to physical processes, facilitated a reimagination of the human torso as a topographic site for deeper material exploration and application, offering several implications across urban landscape design, technology, and material and cultural insight. The outcomes of the digitally scanned torso with methodological use of photogrammetry and 3D modeling can be seen in Figure 5.

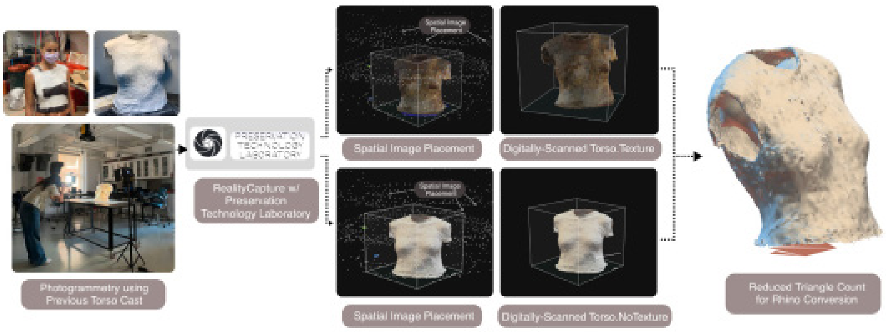


Figure 5:
Physical to digital representations of the scanned human torso.

Linking the human body torso geometry and the urban terrain was created in this study to allow for a speculative design process where the body is expanded from merely a biological entity to a spatial form that can serve as an imaginary landscape. This reinterpretation transforms the body into architectural micro-environments, reframing it as a living, interactive structure that exists in dialogue with its surroundings. By doing so, it bridges the gap between human form and natural systems, creating a dynamic interplay between the individual and the larger ecological or architectural contexts; serving as conceptual nodes that invite new interpretations of scale and function; extending beyond the body to influence the design of landscapes and built environments; and, opening up new pathways toward body and landscape interrogation, as seen in Figure 6. Just as landscapes can be mapped by layers, also the torso may be segmented for multi-material 3D printing, combining textures and structural elements in a single form, building connection between previous boundaries that existed between the organic body and the built environment as a site for investigation.

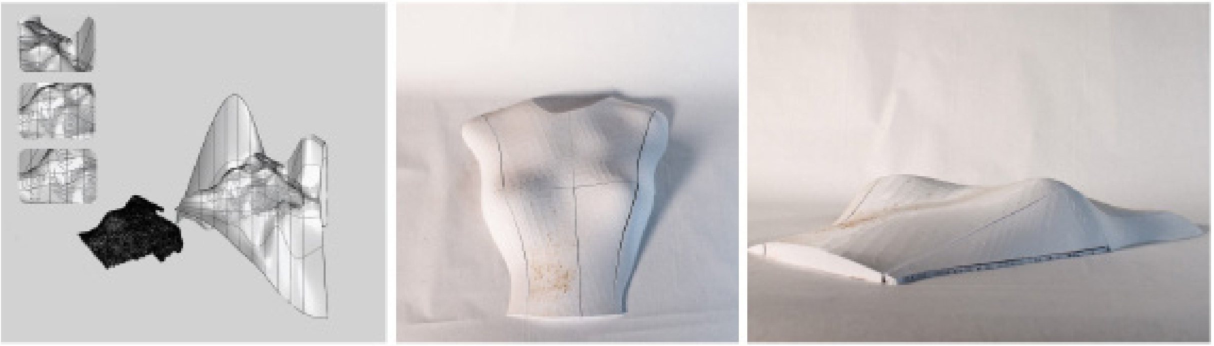
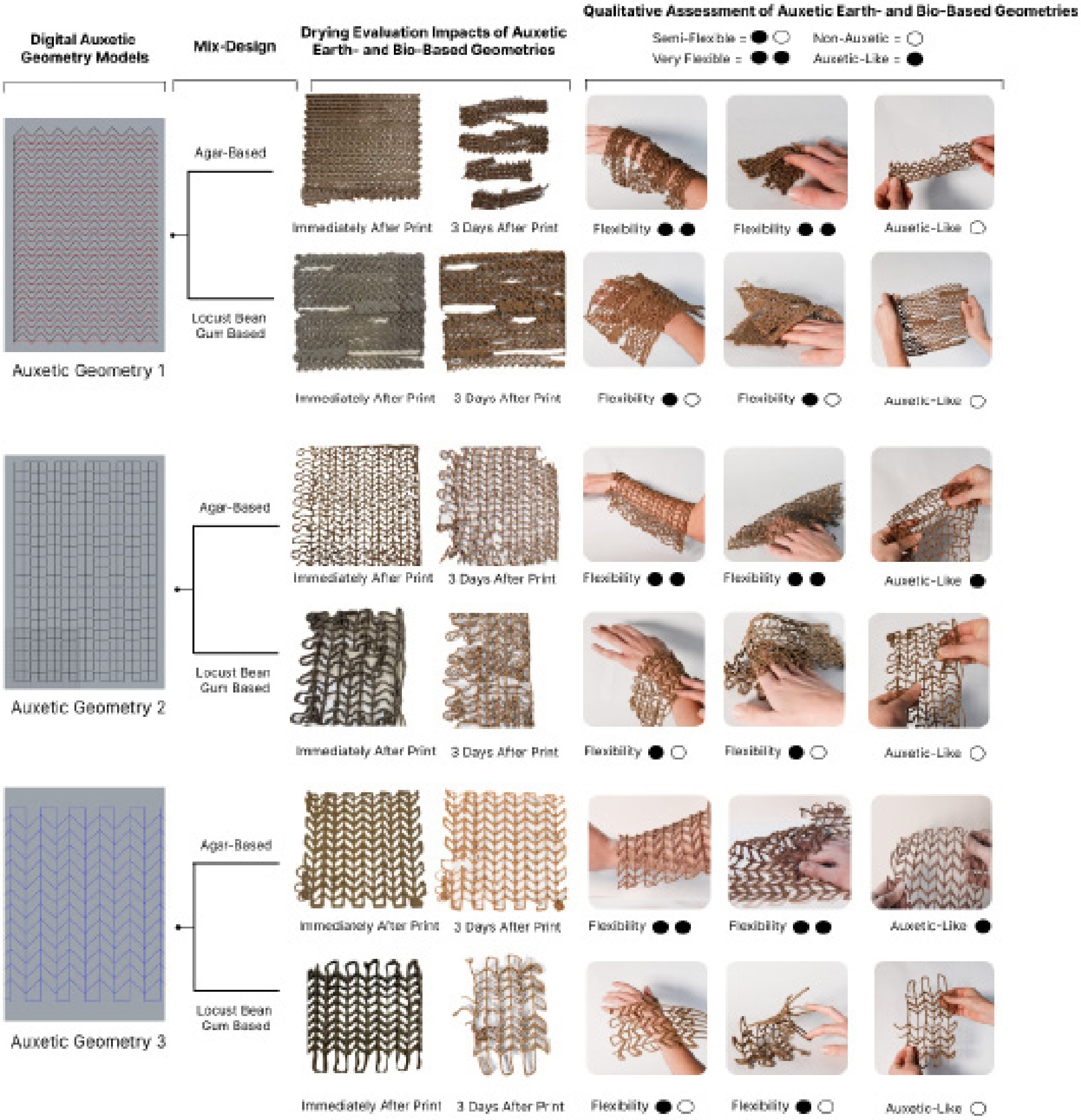


Figure 6:
(Left) Digital Representation of Torso as a Terrain. (Middle - Right) Physical Representation of Torso as Terrain.

The results of the auxetic planar patches showcase a range of earth-fiber textile prints in the form of planar patches conducted to assess material mix-design successes with auxetic geometric variations during initial print tests seen in Figure 7. The printing results compared three different auxetic re-entrant geometries planar patches (Auxetic geometry 1, 2 and 3), with each geometric print compared between two different earth-fiber mix-designs used in previous earth- and bio-based textile applications, an agar based and locust bean gum-based mix-design, to assess how variations in earth- and bio-based mix designs interact with the presented auxetic geometries. Auxetic geometry models (1, 2, and 3) were then analyzed in terms of their drying impact at two stages: immediately after printing and three days after drying which resulted in changing structural and mechanical qualities of the auxetic geometric prints. Finally, auxetic geometries (1, 2, and 3) were qualitatively assessed for their flexibility "semi-flexible vs very-flexible" and "Auxetic-like or Non-Auxetic".

Auxetic geometry 1 was also 3D printed into a planar patch using thermoplastic polyurethane (TPU), a plastic-based material (Backes et al, 2024), to serve as comparison between synthetic and earth-fiber materials in the context of auxetic geometry experimentation as seen in Figure 8.



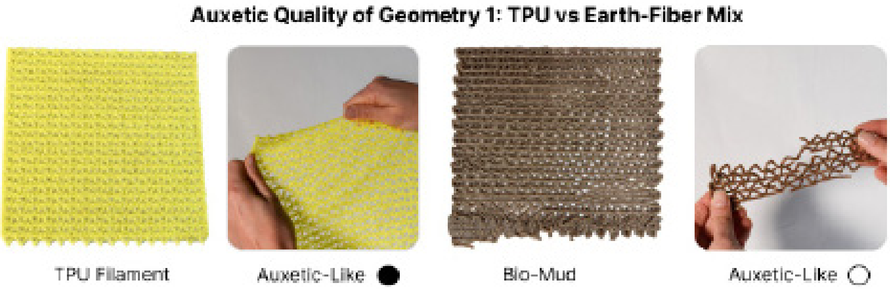


Figure 7:
Matrix of auxetic geometry with earth-fiber mix-designs and qualitative assessments

Figure 8:
Comparing TPU to earth-fiber mix to assess auxetic-like quality of geometry 1.

The resulting structures effectively exhibited auxetic-like properties, confirming the viability of the geometrical design within a synthetic material framework. However, when applied to the earth-fiber mix-designs, Auxetic Geometry 1 failed due to material dehydration, which compromised its mechanical behavior, removing the auxetic-like quality of the final planar patch. This outcome further underscores the need for further optimization of auxetic geometries in relation to the properties of the earth-fiber mix-designs. Specifically, evaluating how the intrinsic qualities of earth-fiber mixed designs —such as their evaporation-dependent curing — may inform the translation from the material scale into the geometrical scale, to foster a deeper material-property-structure synergy.

Unlike petroleum-based polymer and synthetic materials such as the baseline TPU, natural and low-carbon earth- and bio-based -fiber materials geared towards textile design can exhibit variability in their deposit, especially between the connecting nodes or 'bendable ligaments' within an auxetic geometry pattern. This indicates that the design of the auxetic geometry must be adjusted to account for this increased deposit of material in relation to the nozzle size of the printer. Additionally, the material is prone to extensive evaporation and dehydration which further causes variability and lost connection nodes of its structure. During the drying phase, the auxetic patches made from agar and locust bean gum revealed significant material challenges. For example, the agar-based patches rapidly lost connection points due to dehydration, resulting in detachment and a failure to maintain auxetic-like qualities (see Figure 7). While the locust bean gum mix retained more structural integrity and exhibited less dehydration across the three auxetic geometries, the mix-design also proved too stiff for fully flexible applications further emphasizing that the design of auxetic geometries should consider the material nature of the earth-fiber mix designs for most successful results.

Auxetic planar patch observations informed a critical design understanding: the importance of longitudinal connection points with bendable ligaments integrated within the design in creating auxetic geometries with earth-fiber mix-designs. This "woven" adjustment ensured that the material's unique properties could sustain more transverse and diagonal pulls that exhibited auxetic-like qualities, even after dehydration phases, as it provided both lateral and longitudinal strength necessary for the material. For auxetic geometry 3, though the final geometry had longitudinal adjustments, the geometric design didn't have as pronounced of a 'bendable ligament' within its design, showing that though it fit both flexible and auxetic-like parameters, the 'bendable ligament' or longitudinal design in geometry 2 yielded more auxetic-like movement especially when being optimized for earth-fiber mix designs. Ultimately, the decision was made to print auxetics onto a landscape terrain that had both optimized flexibility and most auxetic-like qualities, which led to the decision to print Auxetic Geometry 2 (designed with longitudinal connection points with a bendable ligament that enhanced its auxetic-like properties) using the agar-based mix-design recipe (which maintained flexibility), the planar patch print that was qualitatively assessed as having met qualitatively assessed flexibility and auxetic-like parameters seen in Figure 7.

The final process began by projecting the chosen auxetic geometry onto the torso in Rhino, utilizing the sliced sections of the torso terrain model which were then calibrated to align with the dimensions of the 3D printing bed and the specifications of the z-axis of the printing nozzle. After projection, each individual torso terrain section, integrated with Auxetic Geometry 2, was converted into G-codes which was interpreted by the 3D potter software. The physical torso slices were manually adjusted to ensure alignment with the pre-determined calibration of printing bed and nozzle parameters established during the digital design phase. Following the printing of all sections, the individual components were then assembled to create a cohesive representation of auxetic geometry 2 printed and integrated onto the torso terrain as seen in Figure 9.

Figure 9:
Auxetic geometry 2 printed on torso terrain with agar earth-fiber mix.

4. CONCLUSIONS

The development and testing of earth-fiber mix designs with auxetic-inspired geometries provide valuable insights for their application in textile and flexible membrane designs, particularly when adapted to human-scale wearable forms, but also when expanded to landscape terrain forms. Through iterative 3D printing of auxetic geometries using agar-based and locust bean gum-based materials, this study highlights the importance of material-design specific adjustments, such as optimizing nozzle paths in Grasshopper and accounting for the dynamic properties of natural materials.

These adjustments ensure successful deposition on non-standardized and non-uniform terrains and support the unique performance requirements of earth-fiber mix designs.

The integration of auxetic geometries and mix-design within a digitally scanned torso terrain demonstrates the potential of combining physical and digital workflows within natural material design. This methodology opens pathways for future ready-to-wear innovations and broader explorations of landscape applications, emphasizing the value of these materials for flexible and sustainable 3D printing solutions. Natural earth- and bio-based materials, when paired with auxetic geometries, present exciting possibilities for decarbonized material systems in responsive cities, potentially influencing the design of environmentally friendly building materials and wearable architectural forms.

Nevertheless, future research is still required on the scalability of nonconventional materials and geometries for large-scale applications. Composite reinforcement, vulnerability to environmental conditions, and limitations in automated fabrication pathways require further investigation for broader adoption in sustainable industries. Future research should explore scaling auxetic-inspired earth-fiber geometries to building, urban terrains, erosion while assessing the impact of mix-design and geometric choices across fields such as fashion, industrial design, and construction. These efforts could further unlock the potential of earth-fiber auxetic geometries in developing innovative and sustainable material systems across multiple disciplines.

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