GROW ME A WARDROBE

HOW THREE-DIMENSIONAL BIOFABRICATION STRATEGIES FOR BACTERIAL CELLULOSE CAN REFRAME FASHION PRACTICES THROUGH MAKING AND INTERACTING WITH NON-ARCHETYPAL BACTERIAL CELLULOSE-BASED WEARABLE OBJECTS

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Abstract

With the world in a state of climate emergency, fashion faces significant challenges due to its massive environmental and cultural influence. Clothing accounts for over 60% of textiles, with production doubled whilst use has declined by 40%(Ellen MacArthur Foundation, 2017). Existing linear supply chains leave significant ecological impacts, with waste being a predominant factor. Rissanen (2013) estimates that 15% of fashion waste occurs during garment assembly. Given the complexity of textile and fashion industries parallel to rising environmental degradation, multilevel solutions are crucial to ease environmental strain. This study aims to bridge the gap between fashion and textiles by employing bacterial cellulose growth patterns to create textiles imbued with fashion attributes, focusing on form as the main designable quality. Fabrication is recorded and evaluated through contextualisation during body-artefact juxtaposition in workshop contexts, aided by visual and written documentation. The output consists of two artefact series illustrating proposed biofabrication methods bridging fashion and textiles, augmented by a revised methodological flow informed by resulting design process and material outcomes. Contextualising biofabrication in practice and prolonged interaction expands possible ways of making, dressing and embodying unconventional aesthetics, resulting in more prosper forms of fashion.

Keywords: *Bacterial Cellulose, Biofabrication, Three-dimensional growth strategies, Multi-species Interdisciplinary Design, Regenerative Fashion Systems*

INTRODUCTION

With the world in a state of climate emergency, fashion faces significant challenges in curbing hazards consequence of production due to its massive environmental and cultural influence. Clothing accounts for over 60% of textiles, with its production doubled whilst use has declined by 40%, mainly due to fast fashion (Ellen MacArthur Foundation, 2017). Existing linear, segregated supply chains leave significant societal and ecological impacts, with waste being a predominant factor amongst several others (Ahmed et al, 2023; Ellen MacArthur Foundation, 2017). Rissanen (2013) estimates that 15% of fashion waste occurs during garment assembly. Given the complexity of textile and fashion industries parallel to rising environmental degradation (Mikulčić et al., 2022), holistic, multilevel solutions are crucial to ease environmental strain.

Addressing such wicked problems highlights the importance of the framework contextualising fashion's many design-make chain links. As deep enmeshment between fashion and humanity within larger ecosystems becomes recognised, arguments supporting "perspective[s] that transcend anthropocentrism to ensure collaborative survival" become consequential. Designing beyond the human implies interacting with the non-human, a relationship that, within the scope of fashion, has delivered reciprocal benefits by producing textiles and materials with enhanced properties (Phan et al., 2024), novel manufacturing methods (Arnadottir et al., 2022; Arnadottir et al., 2021) and potential for environmental safe-guarding (Groutars et al, 2024).

BACKGROUND

Despite the desirable alternatives afforded by biomaterials' ecological advantages to fashion and textiles, their functionalisation, industrial adaptability and dissemination remain unconquered. Novelty and curiosity have motivated a plethora of innovative forays into grown design, which struggle to break into existing fashion landscapes as current fashion industrial complexes have not been built to contend with the autopoiesis of biomaterials, instead framing the process integrally through anthropocentric perspectives (Camere and Karana, 2017).

Manufacturing (bio)technologies

BC commonly presents as a flat sheet interfaced between culture and oxygen, and has primarily been investigated as such. Growing interest in biodesign and livingness (Karana et al., 2020) has led scholars and practitioners to challenge the prevalence of this form, probing for alternative ways of creating more complex structures and fabrication pathways.

Derme et al. (2016) developed three-dimensional BC membranes by combining biosynthesis, digital fabrication and computational modelling, demonstrating novel techniques of in-situ self-assembling, as well as relevant biocompatible scaffoldings. These methods clarify which factors affect BC' biological pathway by altering the membrane's physical qualities, suggesting enhanced and new functionalities. Including complementary technologies, such as scaffolds, demonstrate that BC is modifiable during growth and fermentation, and may benefit from synergistic interaction with complementary technologies towards conceiving three-dimensionally fabricated artefacts.

Relinquishing complementary technologies as integrated part of the outcome, Arnadottir et al. (2022) propose principles for a microbial 3D printer, consisting of a bioreactor operated through digital and biological inputs where BC growth was modulated through interaction with other non-human entities, in this case, Escherichia Coli. Interspecies interaction in-vitro sought, firstly, to modulate growth by dripping cellulase onto the surface of the BC membrane with a robotically controlled syringe head; and secondly, to develop a method similar to stereolithography by projecting Z-axis slices of a 3D digital model onto light-responsive E. Coli cells, which in turn modify the growing pellicle.

These projects elaborate on autopoiesis beyond techniques resembling cut-and-sew practices, and leverage growth in synthesising three-dimensional prototypes. Ultimately, both centre material engagement with BC's biological processes in a designerly manner, but are still subject to the limitations of small-scale production, as well as rapid decay without finishing processes deterring the effects of dehydration (Phan et al., 2024).

Turhan et al., (2022) challenge these limitations, as well as formal and technique complexity by proposing a composite formulation of BC adaptable to 3D print methods and hardware. Attempting to compensate for BC's shortcomings as a design material by introducing supplementary materials to create a composite suggests ways that BC properties may benefit from synergistic material entanglements, lending itself as a valuable resource across design and fabrication fields. The artifactual results show that compounding BC with pectin and jute fibres "enhanced the structural load-bearing capacity of the overall form", suggesting potential design-make innovations by using bioactive compounds, as well as a departure from the long-established membrane form that BC is often analysed as.

Expanding possibilities of what can be designed with BC requires shifting towards collaboration where BC biological patterns may flourish in making artefacts, which requires understanding its agency and sensitivity, given that BC has the ability to perceive surrounding stimuli (Karana et al., 2020). Dynamic behavioural response unfolding into design expression highlights the importance of temporality and reciprocity as elements of experienced materiality. Being rooted in habitability and relation with other external entities, co-designing with living non-human entities demands a degree of intentional interaction, which carries its own set of idiosyncrasies.

Interaction

Giaccardi and Karana (2015) lay out a framework to discuss "how materials shape ways of doing", articulating the malleability of practice relative to materials experience according to configurations, levels and patterns of experiential proximity. Drawing attention to the link between material aesthetics and performance, basing repeated interaction in the unique properties of a given material produces unanticipated practices, an effect exacerbated by acknowledging non-human agency. Karana et al. (2020) elaborate by emphasising the importance of careful crafting to attend to livingness when designing material qualities with artifactual results as an active phenomenon. According to the actors, numbers, temporalities and spaces in which interaction occurs, Groutars et al. (2024) expound on possible types of interspecies relationships, proposing the adoption of alternative mindsets that embrace such emergent aspects of designing with nature, specifically unpredictability and dimensional variety. As this directly opposes fashion's conventional tenets of perfection and systematic production, examining artefact and practice in parallel is key to establishing potential pathways for designing collaboratively with the non-human, specifically BC within the scope of this research, as an agential stakeholder as well as a design artefact.

APPROACH

As "things do not exist in a vacuum; rather, they are embedded in different relations, configurations or networks that determine how they are interpreted" (Wakkary, 2021), slightly tweaking existing design practices to accommodate living materials would hinder the experiential dimensionality of co-designing with non-human entities. Investigating a field where an artefact's inextricability from the body (Geczy, 2019) and subsequent material perception (Biofabricate, 2020; Ahmed et al., 2023) generate intricate, manifold layers of interpretation, understanding human-technology-context relations and their influence over artefact significance and contextualisation (Rosenberger and Verbeek, 2015; Wakkary, 2021) is paramount to achieving effective design strategies and their intelligible expression.

Things, or technologies (Wakkary, 2021), co-shape many facets of human experience; how we perceive our environment, our situated sense of self, and how we navigate it (van der Zwan et al., 2020). Given an artefact's multistabilities and mediating roles, a critical reflection on iterative practice hypothesising through prototyping (Rosenberger and Verbeek, 2015) addresses both theory and practice indispensable to establish foundations for fashion systems tailored to BC's biological patterns. Incremental and cyclical construction of prototypes exploring BC crystallises understanding of textile technologies of these living textiles whilst building knowledge of ways of designing and wearing them (Koskinen et al., 2011), creating a generative symbiosis between 'what', and 'where' and 'how' of BC artefacts. This addresses potential materialities of crafting BC artefacts embodied within practice stemming from performance and collaboration in making and wearing (Giaccardi & Karana, 2015) these artefacts.

AIM

BC's autopoietic aptitude opens up the elements employable to achieve design expression beyond what is feasible for traditional textiles, blurring the line differentiating material and product, even offering variety in how this is accomplished (Groutars et al., 2024; Camere & Karana, 2017). Textiles are hereby interpreted as processed design materials without application-specific features, whereas fashion is defined as textile given specific attributes enabling wearability.

This study aims to bridge the gap between them by employing organic growth patterns of BC to create textiles directly with fashion-specific attributes designed through body-artefact interaction. These textile-fashion hybrids focus on form as a designable element without resorting to archetypal garment configurations. The resulting artefact collection ultimately seeks to reframe conventions inherent to making and wearing fashion by positing these acts as interface contextualising BC's organic materiality within the human body.

MATERIALS AND METHOD

As the overall process investigates production methods derived from BC's autopoiesis, the design process progresses from small-scale material sampling to full-fledged artefacts examined through situated interactions to effectively analyse resulting and future design expression. The fabrication process concerns prototyping with BC towards achieving form through material rigidity. Smaller samples testing various degrees of this property gradually upscale in size and interactive potential, providing a progressive, materially-informed and practice-based exploratory expansion from textiles into fashion objects (Markussen, 2017).
Augmenting prototype size requires design choices to be made, which are here deduced through interaction directing possible and desirable design pathways. Contextualising the material outcome as an empirical base for fashion practices reciprocally reflects on human-artefact interac-

tion of BC textiles through a post-phenomenological lens (Ritter, 2021), subsequently elucidating how interaction can enhance materiality towards bridging the gap between textiles and fashion through embodiment acts.

The research concludes by proposing strategies reinterpreting fashion according to observed BC qualities. Designing with agential materials broaches speculation regarding ways in which textile-fashion hybrids can be interpolated within design-make cycles and their transformative effect on practice (Giaccardi and Karana, 2015).

METHOD

Given that this study establishes 'defined attributes enabling wearability' as differentiation between fabric and garment, understanding what designable features configure the development of BC textiles and which are responsible for enabling wearability becomes crucial. Previous explorations regarding fashioning methods for BC (De Lara, 2024) identify two fabrication methods through which BC's autopoietic nature is best leveraged; A) through composites employing knitted scaffolds where BC is applied and reassembled; and B) direct, selective manipulation of processed BC fibres. De Lara (2024) also identifies 'colour', 'form' and 'texture' as key designable categories of textiles and garments.

Aldrich (2020) stresses the importance of the body's three-dimensionality when translating flat patterns to finished garments, stating that "the garment's success and originality rests with the quality of the pattern cutting" when discussing methods of creating shape. 'Form' is thereby interpreted as the principal property transforming fabric into garment as it limits which entities the resulting garments may be juxtaposed against, whereas 'texture' and 'colour' don't pose such strict limitations. To streamline the obtention of form, proposed incremental size and interaction variation suggest sequencing the experimental flow as follows:

a) Sampling; b) Prototyping; c) Artefact development

In understanding how resulting artefacts may be worn de facto or fledged into full garments, interaction and embodiment acts flesh out the semiotics implicit in working with BC within the realm of human garb. These acts therefore become the probing tool of design of this study, informing the progression from Prototyping to Artefact Development, and later aiding in evaluating Artefact Development as a conclusion, as well as leaving open-ended proposals for future design (Fig. 01) described in section *Discussion*.

Biofabrication

Sampling: From the overarching category of form (De Lara, 2024), 'rigidity' was selected as the tested variable designing form enactment due to its unusual tactility and textile manipulation potential. BC pellicles were processed using a domestic food processor, producing a fine paste. Water content was partially extracted from the paste at (a)0%, (b)25%, (c)50%, (d)75% and (e)90% volumes, creating biofilms of 50mm thickness when wet. The resulting paste samples were then poured in 80mm x 80mm PLA molds, allowed to reassemble for 36 hours, then air-dried at room temperature ±25ºC (Fig. 02). Conclusions from this stage are applied during Artefact Development as a finalised design; exploratory experimentation of Prototyping phase is realised using wire as temporary tools enabling BC rigidity.

Prototyping: In order to analyse how rigidity would influence textile form, four different crocheted scaffolds were produced with two linear and circular configurations each (Fig. 02). Sub differentiation in scaffold morphology examined the overall formal variation and potential emergent embodiment patterns during interaction.

Scaffolds were autoclaved at 121ºC for 15 minutes and blocked at room temperature ±25ºC. BC paste with original water volume was applied to the upside, covered with saran wrap and left to reassemble for 48 hours. This process was repeated with the underside of each prototype before uncovering and air-drying.

Wires (ø 10mm, ø 8mm, ø 6mm) were placed against structural crochet lines and loosely sewn to emulate results from Sampling stage, enabling form manipulation and implicit artefact investigation probing for designerly expression. Resulting prototypes were placed within a workshop context, where participants were invited to probe and interact with them to explore materiality, properties and situated expression. This process is described in subsection *Embodiment as Design Tool.*

Artefact Development: Photographic, video and written documentation from the Sampling phase and workshop session contrasted with documentation of the making process and the author's own reflections were examined using

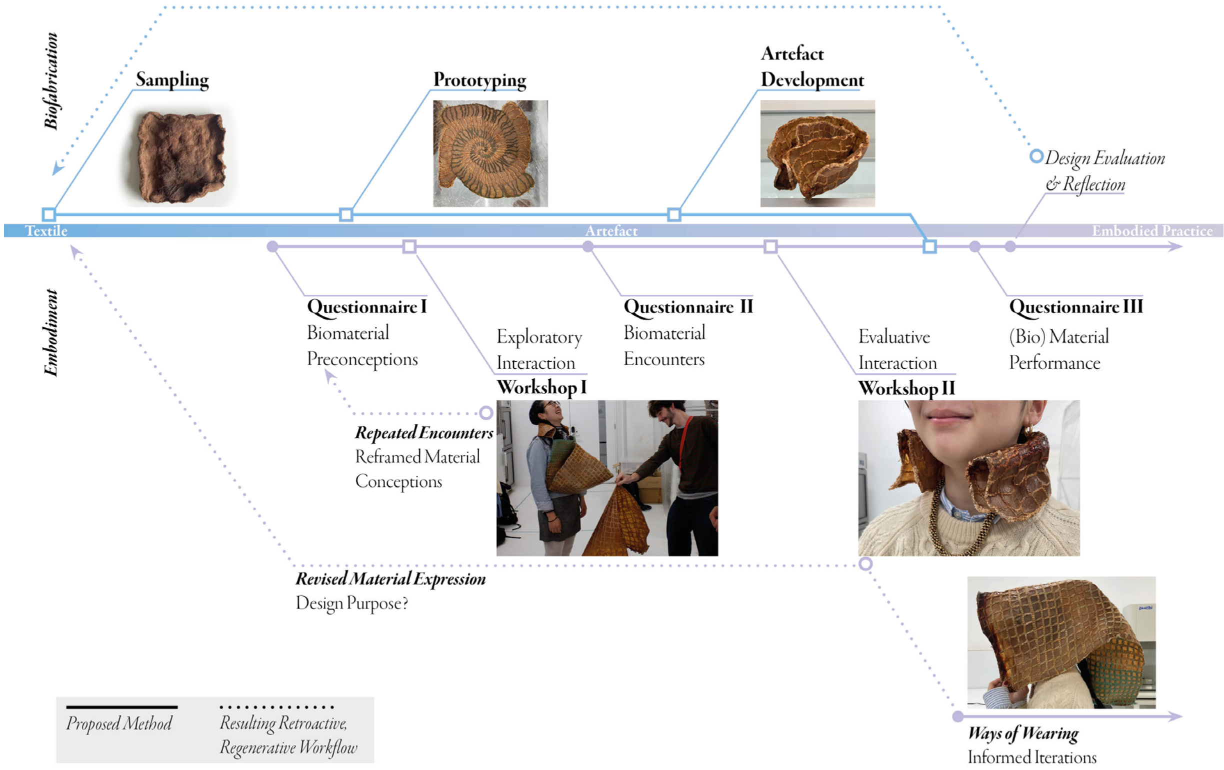
Biofabrication
Sampling
Prototyping
Artefact
Development
Design Evaluation
& Reflection
Textile
Artefact
Embodied Practice
Embodiment
Questionnaire I
Biomaterial
Preconceptions
Exploratory
Interaction
Workshop I
Questionnaire II
Biomaterial
Encounters
Evaluative
Interaction
Workshop II
Questionnaire III
(Bio) Material
Performance
Repeated Encounters
Reframed Material
Conceptions
Revised Material Expression
Design Purpose?
Ways of Wearing
Informed Iterations
Proposed Method
Resulting Retroactive,
Regenerative Workflow

Fig. 01

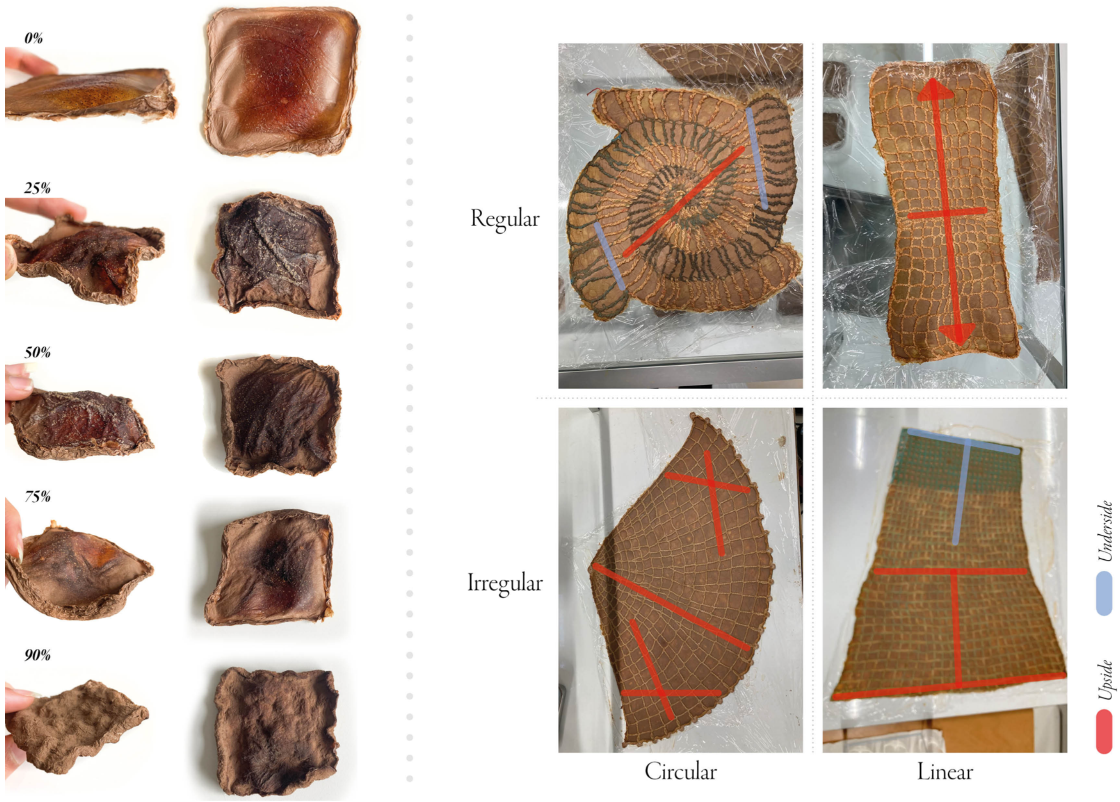
0%
25%
50%
75%
90%
Regular
Irregular
Circular
Linear
Underside
Upside

Fig. 02

the annotated portfolio method (Gaver & Bowers, 2012) to capture not only material conclusions, but to discern experiential patterns arising from the prototypes. Conclusions from the annotated portfolio served as tool to design the finalised artefact forms.

Sought forms compounded desirable aesthetics with the most prolific performative interactions explored with workshop participants. Once each design was decided, wires were shaped into the desired form for posterior BC application. In preparation for this, prototypes were partial rehydrated with a water mister to enhance the fastness of new BC applied over the surface. Processed BC with the desired rigidity was then manually applied over the structural scaffold lines to retain the shape effected by the wires, covered with saran wrap for 48 hours and air-dried at room temperature ±25ºC.

Embodiment as Design Tool

In a workshop context, five participants were invited to interact with the wired textiles in an exploratory capacity. Resulting encounters (Fig. 03; Fig 04) were documented through photography and video, as well as written records accompanying human-textile interplay. Interaction first examined the prototypes as insular technologies segregated from the body, prompting conversation about their disembodied textile properties. Participants were encouraged to sense and manipulate the textiles freely, and discuss findings and curiosities with one another. Artefacts then came to be interpreted as embodied textile, encouraging participants to juxtapose human and artefact through draping on the body, seeking possible, potential and desirable ways these artefacts could be worn. Once the session concluded, participants were asked to reflect on the session and retrospectively exploring encounters and performative experiences through a written questionnaire.

Documentation from this session was contrasted with participant's questionnaire responses to determine possible, preferable and desirable material qualities correlating to performances unfolding into peculiar "ways of doing and their assimilation into practices, […] mediated and affected by the material character of such performances" (Giaccardi & Karana, 2015). The decided forms were then permanently enacted in the prototypes as described in Artefact Development subsection.

In a second workshop session, the original participants were invited to review the artefacts' finalised form in order to examine how bodies interact with intentionally-made BC objects, and elicit ways of wearing. This phase targets the performative embodiment of non-archetypal artefacts through practical speculations about ways of wearing from knowledgeable perspectives by probing for interaction rooted in material character and previous material encounters. This contextualisation seeks to reveal potential future ways of wearing, as well as how the act of wearing can reciprocally inform ways of designing tailored to BC morphology.

MATERIALS

Selected materials are composites of BC and crocheted yarns. Output is recorded through photography and video, and supported by written documentation of the make-design process.

Bacterial cellulose pellicles were obtained through a modified Hestrin and Schramm medium (De Lara, 2024) synthesised, processed and reassembled (De Lara, 2024) at the Biomaterial Factory in Kyoto Design Lab. Yarns were purchased at Daiso Japan, and are 100% cotton, 50% of which labeled recycled.

RESULTS

Material output consists of two prototype series testing rigidity and enacted form, and were fabricated employing BC autopoiesis combined with human intervention. From a processed (De Lara, 2024) state, they successfully reassembled into textile-like materials, with virtually no waste from either BC pellicles or knit, as well as scarce energy and manufacturing resources - these limited to use of a domestic food processor and human labour. This demonstrates how leveraging organic properties of BC, amongst other biomaterials, can bridge the divide between textile and fashion, reducing waste across supply chains, as well as delivering novel material expressions articulating emerging design narratives.

Sampling stage (Fig. 02) tests reassembled successfully, with 25% and 50% water volume removal displaying the sturdiest results concerning the reassembly process. Surfaces on the remaining sample present more irregularly; 0% sample shows uneven BC fiber arrangement due to irregular water evaporation rate within the mould. 75% and 90% samples required manual kneading into the

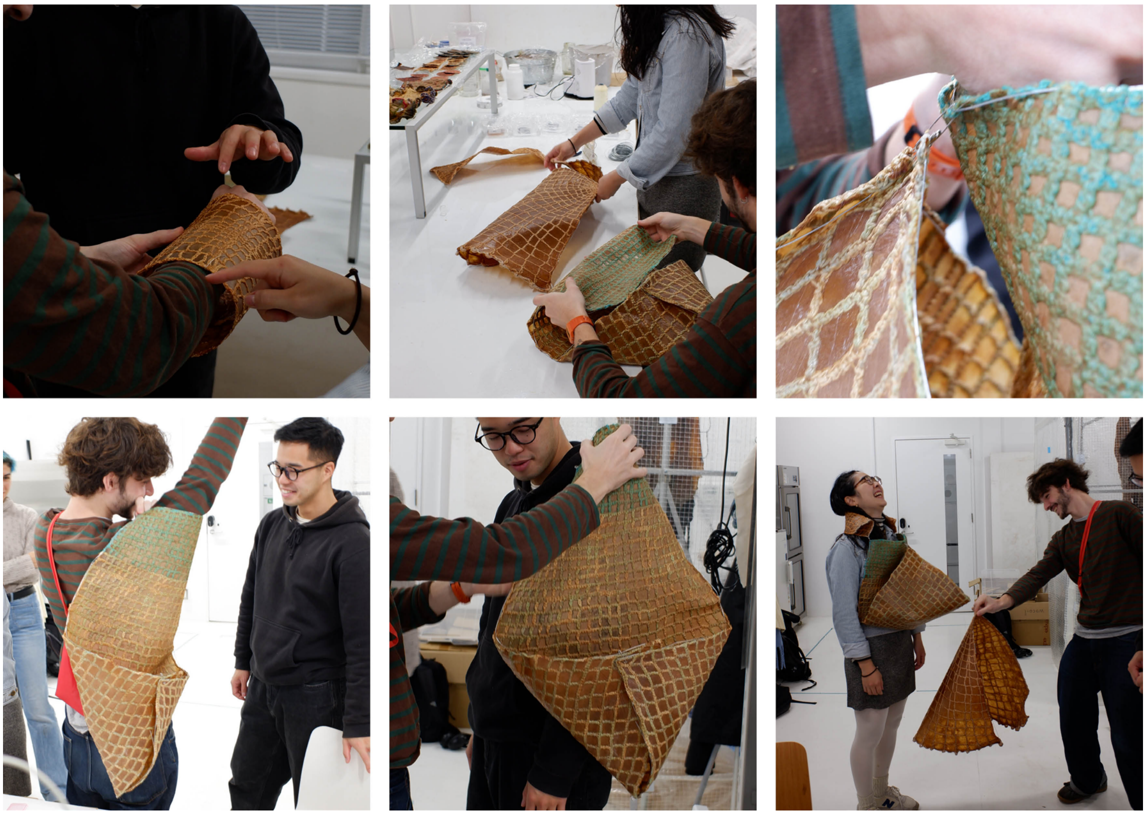

Fig. 03

Fig. 04

mould, resulting in slight variations in thickness and surface smoothness. Evidence of shrinkage becomes obvious as more water volume was removed, as well as warp distorting the initially flat sample. There doesn't appear to be a recognisable pattern in the warp, nevertheless, control over warp through design interventions and actors in this type of expression are elaborated on in the discussion section.

The fabrication method hypothesised that BC paste with removed water volume would modify unaltered BC paste, however, upon application and posterior drying, the rigid BC paste failed to attach securely to the unaltered prototype. The dried rigid paste was rehydrated, reprocessed and reapplied to its original location with increased manual pressure, as well as sealing the plastic wrappings in place for drying in order to prolong the drying period, thereby increasing the time that moisture would have to transfer between dry and wet paste and ensure attachment.

When upscaled prototypes (Fig. 04) combined unaltered and reassembled BC, warp became more evident across artefacts, occasionally distorting forms given through shaped wires. This demonstrates dimensionalities perceptible through X, Y and Z axes even when designed flat, which, from designerly perspectives, opens up discussions regarding definitions of three-dimensional textiles contrasted with that of garments. The warp present in the rigid BC areas affected the remaining textile gradually, as the separation between rigid and intact BC applications became blurred upon rigid BC application, indicating bacterial engagement from both densities applied and conforming the textile.

DISCUSSION AND CONCLUSION

This research represents a first step towards compounding textile and fashion design by endowing textiles with garment characteristics. Material testing confirms the feasibility of such hybrid stage, revealing design potential in the act of embodiment by augmenting its aesthetic expression through intentional BC-human interaction (Fig. 01). Future design directions fusing textile and fashion towards garment production may benefit from applying design expression conclusions at early-stage material planning, rather than waiting for end-of-growth phases to then modify the material outcome. This will require anticipating the behaviour of the non-human and contending with unexpected artefact outcomes, which further questions how and whether producing such prototypes could or should be scaled up.

Early-stage material planning, combined with findings surrounding fabrication processes, suggests reconsidering step order. This study concludes that more effective ways to build form through textile making would be to fully dry the prototype only after all BC layers have been attached and shaped. Another consideration would be to switch the order of steps; applying rigid BC paste before fully coating the prototypes with unaltered paste. This reorganisation addresses the difficulty in compounding wet and dry pastes manually, and proposes that unaltered paste may be more effective in encapsulating and supporting the shaped, rigid BC paste, instead of attempting to modify the form of unaltered paste by applying rigid paste.

Human-bacterial interaction takes many forms, several yet unknown or not understood, but a common element of design leveraging interaction as a fabrication method is that these interactions occur across timelines. As opposed to traditional, extractivist methods where material is harvested before processing and manufacture begin, this type of collaborative design relies on growth and regeneration throughout the fabrication process. This means that material will be obtained in 'on-demand' bases, and calls the question of what and when is being made, as bacterial growth can be interpreted as a form of design expression - roughly translated to human terms. Engaging with bacterial growth from a human perspective demands contention with unexpected outcomes of growth and stimuli responses, as well as broaching agency as a design element through intentional crafting of temporalities.

A key problem biodesign must address is its application to large-scale outputs (Groutars et al., 2024; Arnadottir et al., 2021; Biofabricate, 2020), whether this be by introducing facilities and tools adapted to interspecies collaboration (Arnadottir et al., 2022; Turhan et al., 2022), or devising fabrication methods enabling large scale fabrication within temporalities appropriate to produce biological responses (Karana et al., 2020; Giaccardi and Karana, 2015) towards material expressions. Autopoiesis has been here investigated successfully through additive manufacturing approaches, revealing a possible way to enhance textile economising during manufacturing. Creation of form has further shown variation in texture, which may be translated into a number of components across garment archetypes, which require individualised, dual exploration to achieve performance and artistic standards beyond the production of flat, soft textiles.

Participants appeared reluctant at the start of initial encounters, but display a higher level of interest and curiosity as this encounter is prolonged, and becomes performance (Fig. 03; Fig. 04).

Vocabulary featured heavily in workshop discussions in, for instance, describing assembly as 'grown' or 'constructed' rather than 'sewn'. This suggests that a lack of specific wording and material knowledge may hinder audiences from interacting with and expressing curiosity for this and other living materials. During the first workshop, participants seemed more focused on coming to grips with the material, basal assembly techniques, growth methods and material properties, especially regarding texture. Draping attempts were done mainly on extremities, only shifting to participant's torsos towards the end of the first session. Proposed artefact uses centred accessories rather than close-fitting garments. However, during the second session, participants inquired about potential ways of permanently joining these prototypes, or hypothetical duplicates, into larger artefacts through traditional cut-and-sew techniques, bacterial-based joinery systems or modular design, suggesting an amplified ability to envision full garments and outfits constructed using this biofabrication method. Their draping evaluations verified the previously selected design forms, and quickly shifted to more draping explorations starting at the torso and progressing to the head, which hadn't arisen as an option previously. Additionally, when discussing potential artefact uses, participants identified specific existing uses where BC artefacts could be potentially used; furoshiki, business card holders and headgear for Awaodori dance festival. Context of proposed artefacts involves a degree of material and artefact care, as these belong in well-regarded contexts, suggesting positive attitudes towards BC material after having interacted with BC prototypes.

Currently, the interaction involves a BC-produced object, but explores aesthetic expression from a post-growth perspective, without living bacteria. Amongst workshop participants' reflections, the possibility of human and bacteria coexisting in living states was brought up during the second session. This was followed by discussing the purpose of maintaining artefacts alive, concluding that it could be a useful endeavour although they struggled to imagine specific, detailed contexts involving fashion Regardless, potential future uses for symbiotic wearing were enthusiastically encouraged. Possible novel design forms could call for maintaining BC alive by shifting interspecies interaction from commensalistic to symbiotical, especially concerning repair through regrowth strategies, as observed in architectural (Arnadottir et al., 2020) fields. Furthermore, as living material properties continued to be discovered and understood, the possibility of live usage applied to fashion can't be discounted until more profound conclusions are drawn from an integrated science and design approach. In the case of fashion, the proximity of the human body to bacterial source implies challenges for consumer acceptance which design must contend with for this path to thrive.

While this study suggests rearranging the fabrication steps, it successfully delivered textile-fashion hybrid prototypes, positing how autopoiesis may reduce fashion waste. In contextualising, participant interaction reveals increased human-artefact interaction as BC familiarity nears performance (Giaccardi and Karana, 2015), positively correlating sustained interaction with design iterations. Finally, following the variety of potential design avenues specific to each artefact, the result broaches the topic of scalability, not in size, but intentionality, as well as purporting individualised purposes for each artefact.

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CAPTIONS

[Fig. 01] 'Sampling' (left) and 'Prototyping' (right) objects. 'Sampling' objects show different water volumes removed from BC swatches. 'Prototyping' objects show flat scaffolds marked up for BC paste application in preparation for the next stage, artefact development.

[Fig. 02] Photographs taken during workshop sessions, illustrating and detailing the progression of experimental interaction as participants became more familiar with the objects and the BC textile. This progression includes both design development and participant engagement with the biomaterial, where earlier stages represent encounters and later stages align with performances, as described by Giaccardi and Karana (2015).

[Fig. 03] 'Sampling' (left) and 'Prototyping' (right) objects. 'Sampling' objects show different water volumes removed from BC swatches. 'Prototyping' objects show flat scaffolds marked up for BC paste application in preparation for the next stage: artefact development).

[Fig. 04] Diagram of the proposed method and the resulting workflow, outlining how situated expression and interaction enable retroactive and regenerative method loops in material design workflows. Future design directions demonstrate feasible development from material-led perspectives as well as interaction- and context-led experimentation.

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