CONTROLLABLE COLOUR CHANGING MODULAR TEXTILES USING 3D PRINTING AND SCREEN PRINTING FOR ALTERNATIVE SUSTAINABLE FASHION

ADITI MISHRA

Arts University Bournemouth, MADFI, the UK
aditimishra1295@gmail.com
Orcid 0009-0000-3703-0439

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Abstract

The role of technology in fashion no longer remains a gimmick limited to high fashion, eccentricities or fiction. With the advent of wearables and integratable electronics, innovations are shifting the digital fashion paradigm from visual to functional. Meanwhile, the fact that the fashion industry contributes significantly to global emissions and textile waste is irrefutable (Igini, 2023; Quantis, 2018; United Nations Environment Programme, 2018).
Some researchers (Koo et al., 2013; Lang & Wei, 2019; Niinimäki & Hassi, 2011) suggest modular, reusable garments can help counteract the effects of fast fashion. Transformable garments are a potential alternative, but the aesthetics, affordability and functionality limit them from being adaptable to fast-moving trends. (Peter, 2018). A truly transformable garment still lies within the realm of speculations, considering its complexity and limitations of current technology. Cromaflux, is a prototype capable of changing colours as the user wishes, which takes the form of a modular system with varying applications, enhancing both functionality and aesthetics. It utilises 3D printing, traditional screen-printed textiles, and thermochromic elements, allowing for colour changes with smartphone apps. This research aspires to create affordable, adaptable, tech-integrated clothing that defies traditional textile norms, negates the socio-cultural harm of fast fashion, without compromising personal expression.

Keywords: *Digital Fashion; Cromaflux; Thermochromic Textiles; Smart Textiles; Sustainable Fashion*

INTRODUCTION

How many pieces of clothing did you buy this year? Do you remember the exact number? The exact reason for buying what you bought? I believe that as you're reading this, you're trying to rack your brains as to the precise number, and you can't get it right. The pervasiveness and addictiveness of fast fashion are also prompting you to seek justifications for every purchase. According to a report by Uniform Market, adults in the UK have 118 pairs of clothing on average and 60.2 apparel per capita sales volume. (UniformMarket, 2024) Keep in mind that the number is an average, and there are a significant number of people with financial constraints who do not buy anywhere near this number of apparel in a year. The purpose of apparel and textiles in the current global scenario has shifted far beyond the status of a basic human need and has significantly impacted the global stage of resource depletion, waste and climate change (Quantis, 2018). Global emissions from the textile industry will likely increase by 50% by 2030 (Igini, 2023).

The psychology behind fast fashion is explained in an article on the *Sustainable Fashion Forum* from February 2025. Emotional, social, and cognitive factors all play a role in its popularity despite the widespread knowledge of its devastating effects. It is deeply connected to self-identity and expression, and a sense of instant gratification. There certainly is awareness of sustainable practices and their importance;

however, any such conversations usually end up imparting guilt to an average consumer. (Sierra, 2025) Guilt is not a very pleasurable expression to say the least, and serves only to steer the conversation away, or makes people dig their heels in to defend themselves. Something you probably did too when you read the first few lines of my article. So the question arises, how do you change global behaviour without causing a metaphorical withdrawal syndrome of sorts?

HYPOTHESIS AND RATIONALE

The answer I came up with was change. What if we could come up with a textile that could change everything about it every time its owner so desired. What if a garment could change all three, i.e. form, pattern, and colour on demand, without needing to buy anything new? My research is built around this question.

However, does a modifiable colour-changing garment address the problem and is the ability to change a garment enough for the consumer to abandon fast fashion and be satisfied? The short answer might just be "No, not entirely. However, it is a valid alternative."

There is definite interest in sustainable clothing. An article published in the *Journal of Cleaner Production* in 2011 found that 74% of men and 87% of women surveyed were interested in ethical consumption. The study stated that innovative designs that fight against planned obsolescence and also allow personal gratification and self-expression are needed to turn the tables on the trend of overconsumption. Specific strategies they express include modular garments as well. (Niinimäki & Hassi, 2011).

In another research, Koo, Dunne, and Bye in 2013 investigated the feasibility of transformable garments as a strategy to promote sustainable clothing by investigating customer preferences. With the research question "What kind of changeable design functions do people desire in transformable garments?"- the results showed that the most frequently preferred change was changes in colour/pattern and sleeve length (100%), followed by neckline shape and collar type (86%), and silhouette (70%) (Koo et al., 2013). In another study by Chunmin Lang and Bingyue Wei, published in the *International Journal of Interdisciplinary Research*, a quantitative study with 306 female college students in the U.S. was done to examine the predictors of intention to purchase transformable apparel. Fashion consciousness and the tendency for creative choice were two such characteristics that strongly predicted the purchase intention. So, creative, ethical and fashion-forward consumers would very likely take a transformable design positively(Lang & Wei, 2019).

LITERATURE REVIEW

COLOUR CHANGING GARMENTS

I know colour-changing garments are not a novelty. There have been multiple iterations over time. While exploring colour-changing clothing, I saw that the industry was moving in two different technological directions: LED-based and yarn/material-based. Although they had rather different ramifications in terms of sustainability, aesthetics, and practicality, both presented intriguing possibilities.

On the LED/electronic display side, Philips Research Labs created soft interactive displays on the garments by developing soft and flexible LED arrays under the textile surfaces. (Harold, 2006), Joanna Berzowska's Karma Chameleon project produced colours and patterns by weaving photonic bandgap fibres in a lighted jacquard loom (Berzowska & Skorobogatiy, 2009), and an E-ink flexible display on a jacket was developed by E-ink in collaboration with 878co, a Hungarian sportswear producer (Vikarius, 2021).

Although this direction was undoubtedly creative, the very idea of walking around illuminated like a billboard didn't feel rooted in the complex, tactile world of fashion, which is my experience as a textile designer. More significantly, as electronic components may degrade more quickly than conventional textiles, such methods run the risk of leading to planned obsolescence.

So, I decided to look into a natural route instead, using textiles as the colour-changing substance, which I feel can be modified into wearable clothing in daily life and is more aligned with textile craftsmanship.

My interest in this area was sparked by Margaret Ann Orth's PhD research, which questioned the dominant approach of integrating computing technology into everyday objects to produce smart objects, which she found to be ugly, physically ill-suited to their tasks, and lacking the aesthetic and practical goals of designers. She came up with a solution to use textile itself as a computational material, being cuttable, bendable and shapeable and ushered in the era of smart fabrics. She went on to create aesthetically pleasing functional pieces, such as the fabric keypad or musical jackets (Orth, 2001). She also created an art display called the "100 *Electronic Art Years"* that used steel fibres and thermochromic dyed yarns to create a mesmerising display (Orth, 2009). Much of my experimentation is influenced by her work.

In 2013, Lynsey Calder and Sarah Robertson used thermochromic ink and copper heat sinks to create a colour-changing tutu skirt with an origami theme. (Calder et al., 2013). Electrochromic yarns were used to create Ebb fibres for a working textile screen prototype in the Google Jacquard project in collaboration with the Berkeley School of Information (Devendorf et al., 2016). In 2022, a textile capable of changing colour with the help of smartphone apps was patented. Made with thermochromic yarns and heating fibres, it was capable of a certain degree of pattern change (Abouraddy F et al., 2022).

However, none of these innovative creations have really found a large market, as evidenced by their lack in everyday life.

WHY HAVE THEY FAILED?

Despite the apparent interest in sustainable fashion, most modifiable and colour-changing clothing has failed to make it to the mainstream. The reason behind this contradictory statement is multifaceted. An article in *The Fashion Studies Journal* in 2018 argues that, in spite of significant consumer interest, the actual results falter as these designs lack either aesthetic appeal or practicality (Peter, 2018). The complexity in creating these garments presents technical challenges, especially when scaled for industrial production, leading to increased costs and a reluctance for manufacturers to accept these designs. (Varshney & Swami, 2023; Zhang et al., 2025). The washability of any modular textile is always a concern, and especially so for ones with electronic components, as it can impair the functionality and oftentimes special laundering methods have to be used, making it cumbersome or impractical. (Islam et al., 2025; S. Lee & Park, 2024). The durability of various components also adds to the issue pertinent to e-textiles, along with their consistency and stability during use. (Meena et al., 2023). In conclusion, all these designs are plagued by issues of aesthetics, practicality, washability, affordability and challenges in reproducibility. These factors have invariably led to their unacceptance in mainstream fashion.

RESEARCH QUESTION

The research question after all of these reviews was "Can we create controllable colour-changing modular textiles for sustainable fashion and explore their real-world applications?"

OUTCOMES

Considering the previous iterations have lacked practicality, affordability and reproducibility and aesthetics, four major outcomes were expected from the research.

Functionality- The textiles would have to be functional. By functional, I refer to the definition provided by The Britannica Dictionary, which describes it as "designed to have a practical use" (Encyclopædia Britannica, n.d.). That means the textiles should have appreciable functioning outcomes, like being modular or capable of changing colour.

Reproducibility- The textiles would incorporate very basic technologies, making them easily reproducible at the lowest possible costs and needing very little technical expertise

Controllability- Fashion is intimately associated with self-expression. The ability to control that expression is paramount to creating a sustainable garment. The possibility of accurately controlling the look that is created would be the main feature that I believe would attract attention to the textile.

Aesthetics- A significant hurdle in most of the previous projects has also been a lack of aesthetics when it comes to current fashion trends. A part of my project would consider the real-world applications and showcase the various ways they could be used.

MATERIALS AND METHODS

In this research, I developed a modular colour-changing textile prototype through material experimentations, electronic prototyping and digital designing techniques. The system can be divided into 5 interconnected elements, i.e. the fabrication of colour-changing textile surfaces, the integration of resistive heating elements, the electronic control hardware, the development of a user-facing mobile application, and the creation of digital garment visualisations to communicate potential use scenarios.

COLOUR-CHANGING TEXTILE FABRICATION

In recent times, there has been some research regarding creating clothing with 3D printing. (Ge et al., 2023; J. Lee & Lee, 2024; Takahashi & Kim, 2019). I wanted to experiment with 3D printing techniques and use thermochromic filaments and conductive filaments for the material base. However, such techniques and materials come at a high cost, and their availability is limited. So regular 3D printing was used. The chainmail structure was chosen for its flowy nature, which is akin to textiles and the freedom it provides for designing various elements of the chainmail. The small elements of the chainmail could not be printed using PLA printing methods, so instead, SLS nylon printing was used.

For the colour-changing attribute, I used thermochromic pigments. Thermochromic screen printing paste was used based on availability. All methods of dyeing the chainmail with the thermochromic paste failed, so instead, each component of the chainmail was hand-painted. The colours were chosen after mixing and testing on a polycotton swatch. The change of colour was tested using a hairdryer to generate heat. According to the label, the paste would change colour at 45 degrees Celsius; however, in practice, it would change colour at lower temperatures than that. The approximate temperature was around 35 degrees Celsius, which was a good thing considering the human skin perceives temperatures above 45 degrees as hot (Craig, 2009).

I also decided to create another piece using polycotton cloth and screen printing techniques. At heart, I am still a textile designer and working with textiles is just as important to me as researching. A geometric but asymmetrical design on the textile was screen printed. Other components were added by hand embroidery techniques, including the conductive threads. The colour swatches, challenges of dyeing, and initial concepts of 3D printing can be seen in (Fig. 01).

INTEGRATION OF RESISTIVE HEATING ELEMENTS

The functional qualities that the prototype was supposed to have were modularity and controlled colour change. The controlled colour change experimentations were the most difficult to conduct

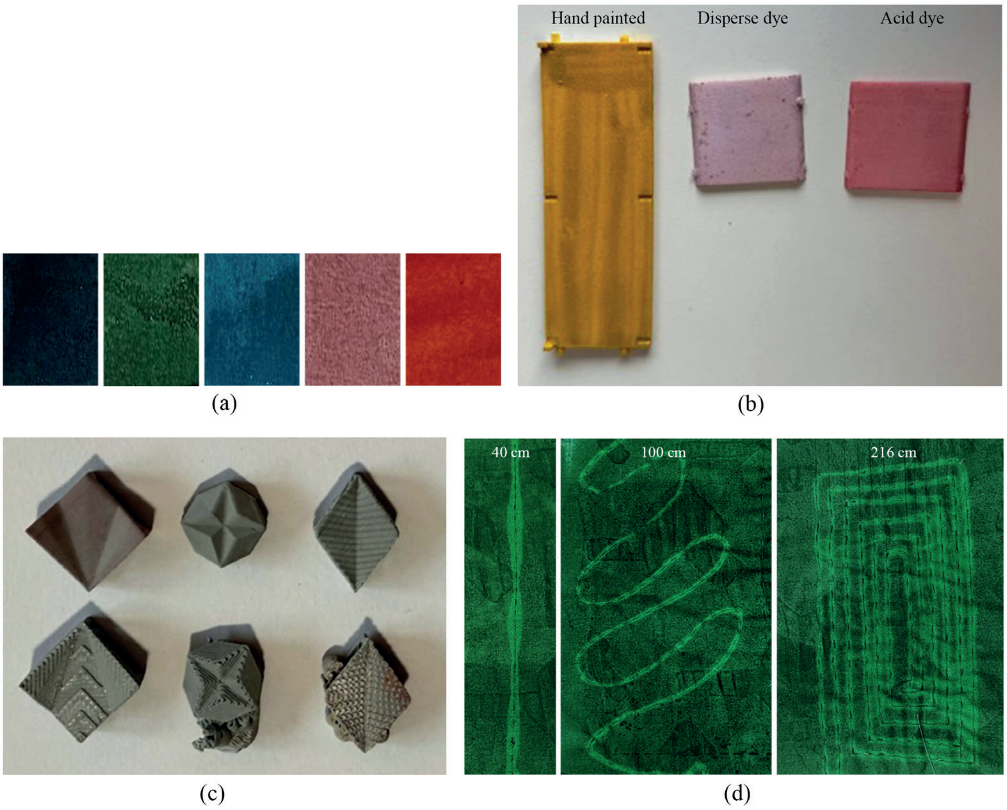


Fig. 01

and obtain. As the heating element, I chose to use steel conductive threads, which are more flexible than other materials and can easily be bought on the internet, and tested them. With the help of the people at the Bournemouth University laboratory, we experimented with the conductive thread stitched onto a piece of cloth coated in thermochromic paste. Stitching was done in 3 different forms, linear, zigzag and spiral, and we subjected them to various voltages and amperages to determine the highest intensity and spread of colour change. It was evident that the most spread was seen in the spiral stitch; however, it also required a significant voltage, as you can see in Figure 01.

The conductive threads were attached behind the chainmail and stitched linearly on the screen-printed fabric, but as predicted, the spread was unsatisfactory. Assuming inadequate heat dissipation and insulation, I added cork-sheets for insulation behind the conductive thread and thermal conductive paste for heat spreading between the thread and the colour-changing surface, which increased the spread of heat, and by extension, the spread of the colour change to satisfactory levels. A 3D rendering of the final schematics can be seen in Figure 02.

CONTROL ELECTRONICS

The control mechanism would enable heating specific pieces of conductive thread as commanded by the user interface app, dictating a change in colour and creating patterns. I used basic, cheap commercial microcontrollers and used two different types to explore various methods of control: one with a Bluetooth unit, and another with built-in Wi-Fi. The power supply was three 3.7-volt rechargeable Li-ion batteries for reusability. The circuit design used MOSFETs for gateways. There were 3 sets of outputs that could be independently controlled to create 7 unique patterns. This number was determined by the output capabilities of the microcontrollers.

USER INTERFACE APP

For the user interface, I created a Bluetooth app for one microcontroller and a web-based app for the Wi-Fi-based microcontroller. Both apps were minimalistic button-based apps with options for various patterns. The buttons function to switch on heating for individual conductive threads at half or

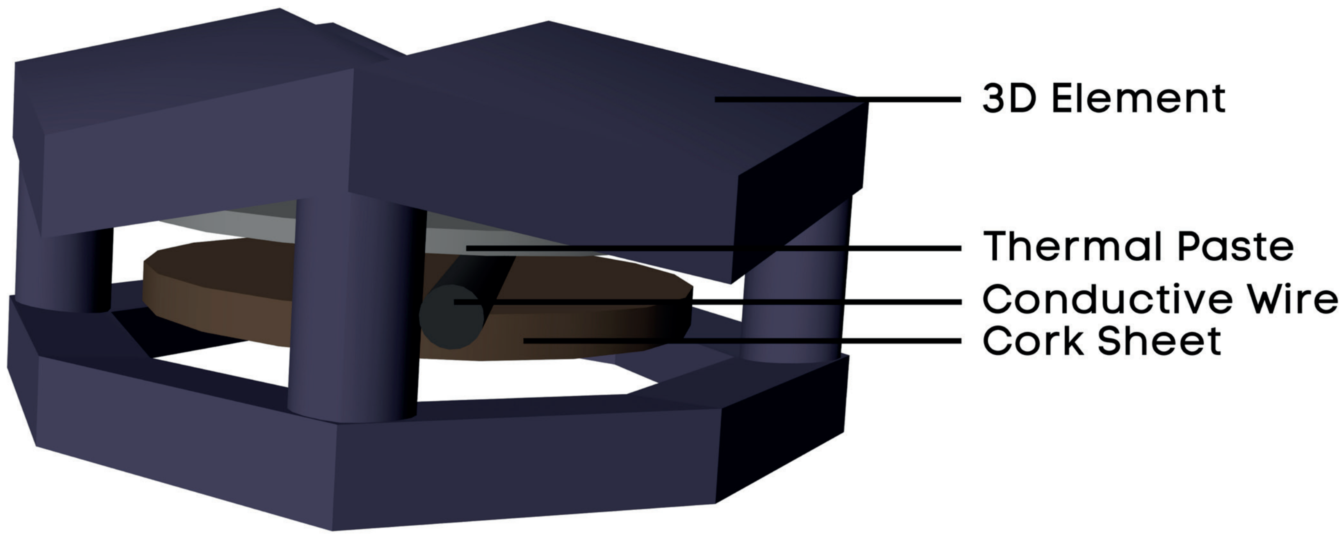


Fig. 02

full strength for testing and control purposes.

DIGITAL GARMENT VISUALISATION

Past forays into colour-changing attire, as previously mentioned, had a lack of aesthetics and practicality. To be able to create complete, intricate pieces of attire was out of scope for this research owing to time constraints. I decided to create virtual depictions of the concept using 3D and virtual reality software. Virtual garments, ads and video depictions of what the final results could be imagined as were created. This enables me to showcase possibilities for this technology and generate an interest in both investors and consumers.

DESIGN CHOICES

There are various design decisions I made at every step that hold some value of expression. The entire research is built to oppose fast fashion and overconsumption while preserving personal expression and design choices. Every part of the design thought process is based on opposing elements. The repeated, sharp morphic motifs in the 3D printed chainmail were meant to reflect the fast fashion cycle. A geometric but asymmetrical design screen printed was meant to symbolise the imbalance between glamour and overproduction in the current fashion landscape. The other components added to the screen-printed textile were to give a definite feminine look. The sharp edges clashing with the shiny pearls and beads were intended to evoke a response from the viewer and represent the clash of glamour and overabundance in fashion. Also, I wanted to incorporate hand embroidery techniques to marry my cultural knowledge to my experiments.

The virtual rendition included bleak, dystopian desert-like future backgrounds to address the grim extreme end result of modern consumerism and greed, while the bright technology-driven actual garment was a classic flowy gown fitted with the futuristic 3D colour changing chainmail as collars and belts, once again conforming with the opposing elements theme.

RESULTS AND DISCUSSION

The major outcomes expected from the research, as previously stated, were functionality, reproducibility, controllability and aesthetics. The prototypes were created after multiple rounds of experimentation and challenges. Despite that, they are still works in progress. 2 prototypes were created in the duration of this research. A prototype made of 3D printed chainmail and another by screen printing techniques on polycotton capable of changing colour with the help of Wi-Fi or Bluetooth connections and an app for control.

FUNCTIONALITY

Both prototypes fulfil their intended functions. The structure of the chainmail provided an aspect of modularity. It was rectangular in shape with dimensions of 30cm by 20cm. It is fluid in structure and malleable, conforming to the body's curvatures. It could be used independently as a sleeve, a belt, or a collar or attached to any other garment structure the designer sees fit. Figure 03 shows the chainmail being used as a halter top on a mannequin.

The screen-printed prototype has geometric but asymmetrical patterns. The patch of textile created could be used as a belt or as a decorative patch on any normal piece of clothing, keeping in line with the modular concept. Figure 03 also shows the belt form and the pattern changes of this prototype.

There was a visible and reversible colour change with 8 unique patterns (with 1 pattern that is its neutral/off state). The colour changes take about 5-7 seconds, depending on the ambient temperature and return to the off state in similar times.

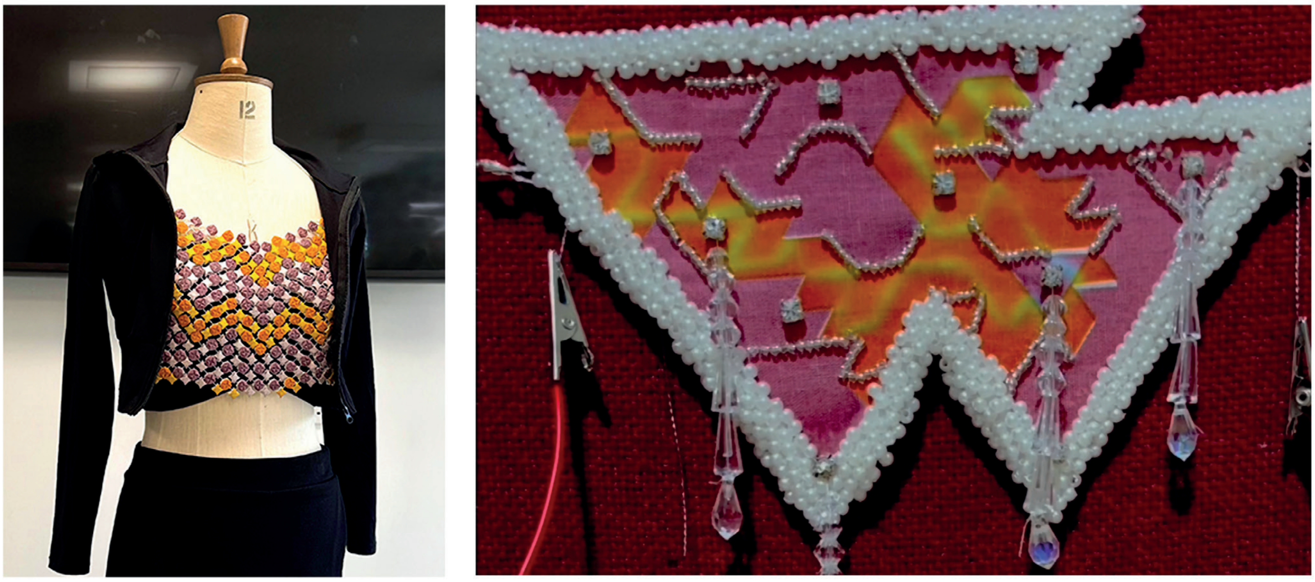
The electronic component, except for the heating threads, can be separated from the actual textile as well, creating a modular controlling unit.

CONTROLLABILITY

The prototypes are controlled using apps, with the 3D printed prototype being controlled by a web-based app and the screen printed prototype by a Bluetooth app. The easiest method to allow users to interact with their device is to connect to it with the help of a smartphone. The Bluetooth app currently has to be downloaded and installed on the user's smartphone, while the web app is accessible by connecting to the microcontroller's wifi and visiting its IP address, which opens the web-based app. The interface itself is minimalistic and intuitive.

AESTHETICS

Aesthetics in itself is a very subjective concept. As I mentioned before, a complete garment using these prototypes was not feasible, so I used 3D and VR software, and AI-generated images to better express



(a) (b)

Fig. 03

their application. I created virtual belts and collars made from the prototype fitted on a flowy gown to showcase its modular use. A fashion ad video of the 3D model with animated colour changes of the collar and belt was also created to further simulate its use in fashion. (Fig. 04) shows the various virtual outcomes of this research.

REPRODUCIBILITY

This entire project was self-funded, except for the thermochromic paste, which the Innovation Studio at Art University Bournemouth provided. It was created using basic 3D printing techniques, screen printing techniques, readily available online materials, and the most basic electronic technology that is readily reproducible and modified as needed. The entire cost of each prototype was under 100 pounds. The prototypes were made from scratch in a university and, quite frankly, in home settings. If mass-produced and automated, the price per unit would be less by a significant fraction. I did require the help of experts in electronics and technology, considering my background in textile design; however, if scaled to manufacturing levels, this should not be a problem.

SUSTAINABILITY

Apart from the proposed outcomes, this technology was created with sustainability in mind. The modular nature of the textile itself is a sustainable alternative (Zhang et al., 2025); however, the carbon footprint is also a significant indicator of sustainability. The textile developed here has an estimated operational carbon footprint of approximately 7 g CO_2 per square foot per wear, based on the energy consumed by pulsed heating (~33 % duty cycle) from a 3-cell Li-ion battery and amortising battery manufacturing emissions over ~300 cycles. This is, however, by no means an accurate number and further research is needed to assess its actual carbon footprint. In contrast, the estimated average carbon footprint for the life cycle of a pure cotton shirt can be up to many kilograms (Wang et al., 2015).

CONCLUSION

Previous iterations of modular or colour-changing garments suffered from a number of faults, including lack of functionality, practicality, aesthetics, reproducibility and affordability (Peter, 2018; Varshney & Swami, 2023; Zhang et al.,

(a)

(b)

Fig. 04

2025). My prototype has tried to address these specific issues in creating a new direction for sustainable clothing.

"*Chroma"* is a Greek-origin English word which stands for colour, and "*flux*" means change. I decided to name the technology Cromaflux as it is a 3D-printed modular textile capable of controlled colour change, the first of its type in the world. Despite its prototype phase, it is sure to herald a change in the future of textiles. It is capable of changing according to fashion trends and allows self-expression by the consumer while being user-friendly, affordable and most importantly, it looks and feels good.

LIMITATIONS

I tried to challenge many of the weaknesses of modular clothing in my research; however, there are still many limitations to my work.

The washability factor is one of the most important factors, especially in e-textiles. I tried to incorporate washable components and made the electronic circuit detachable from the actual textile; however, no laundering experiments were done to confirm the washability and durability of the textiles.

Similarly, dedicated user acceptance studies could not be done to confirm that the final aesthetics would be liked.

The issue of degradation of electronic components, discarding of batteries, and the total average carbon footprint are also yet to be determined, making the question of its sustainability still a topic for further debate.

FUTURE RESEARCH

Further research with experimentation is needed to test durability, safety certifications, and washability. Although the virtual designs allow for the exploration of aesthetic possibilities, more research is needed to investigate user perception and acceptance of both the virtual and the real-world garments created using this technology.

Multiple enhancements and tweaks can be done in the future for marketability as well as diversifying its applications. The product currently exists as a basic prototype. Various, if not all of the components, can be replaced by industrial-grade materials, including commercial-grade insulation and heat spreading materials for more energy-efficient colour change. Miniaturising the controller unit with microprocessors and insulating exposed heating threads would prevent heat loss and maximise safety. Replacing the conductive threads with nichrome or other wires for more efficient heating, covering the chainmail with transparent silicon coating to prevent degradation, and mini solar cells could be integrated in the chainmail to further reduce the carbon footprint. All these changes need further research to finally assess the marketability and practicality of this product.

OTHER APPLICATIONS

Other applications of this research could be in the military or health sectors. It could be used to make dynamic camouflage for both soldiers and their equipment, while it could be used in medicine as heating pads by switching the insulating material for a heat-conductive element to tackle difficult-to-access areas for heating.

The ultimate goal of my research is to create a completely new form of textile that can weather the changes in fashion trends while allowing the users to feel a sense of novelty and change whenever the whim hits. My belief, backed by my extensive literature review on this topic, is that this technology can help curb fast fashion to a certain degree, even if it still needs more research. It is a glimpse into the future of textiles. There is no one answer to sustainability, but I hope my research will be fundamental for its future. I will continue experimenting and refining my product to make it accessible to all.

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CAPTIONS

[Fig. 01] Early experimentations: a) Early thermochromic ink swatch experiments exploring colour mixing techniques, b) Challenges encountered during the initial dyeing process, c) Conceptual development of 3D-printed textile structures, d) Heating trials testing varied stitch lengths and patterns for thermal responsiveness; (Author holds the right to images)

[Fig. 02] 3D rendering of the final schematics; (Author holds the right to images)

[Fig. 03] Final Prototypes: a) 3D-printed prototype top demonstrating modular construction, b) Screen-printed belt showcasing thermochromic colour transitions; (Author holds the right to images)

[Fig. 04] Digital explorations: a) VR visualisation of the 3D-printed prototype (left) and its AI-enhanced rendering (right), b) 3D model illustrating potential applications of the prototype (left) alongside AI-enhanced visual outputs (right); (Author holds the right to images)

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