GRAPHENE-WEAR™

TEXTILES

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Glossary

AATCC	American Association of Textile Chemists and Colorists
BBIA	Bio-Based and Biodegradable Industries Association
BS	British Standard
CGC	Cambridge Graphene Centre
CEO	Chief Executive Officer
DTG	Direct to Garment
EN	European Standard
FFP	Filtering Facepiece
GEIC	Graphene Engineering Innovation Centre
GOTS	Global Organic Textile Standard
G-W	Graphene-Wear™
ISO	International Organisation for Standardisation
MRSL	Manufacturing Restricted Substances List
OAR	Open Apparel Registry
PPE	Personal Protective Equipment
RCA	Royal College of Art
R&D	Research and Development
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
rPET	Recycled Polyester
UKAS	United Kingdom Accreditation Service
UV	Ultraviolet
$\dot{V}O_2$ max	Maximal Oxygen Consumption
WIRA	Wool Industries Research Association
ZDHC	Zero Discharge of Hazardous Chemicals

Introduction

Graphene and related materials are relatively young, but have an enormous potential to lead the technological transformation that can reshape the textile industry [1]. Graphene has exceptional mechanical, optical, thermal and electrical properties and is chemically inert and stable. As a result of these properties and many others, graphene has become the subject of intense interest in the areas of textiles with improved durability, thermal and moisture management, smart, multifunctional textiles and also those with embedded wearable electronics and sensors.

Graphene products have gradually been entering the textiles space in recent years; customers are increasingly looking for convenience, personalisation, multi-functionality and evidence of sustainable materials, whilst many textile and garment manufacturers, designers and brands have embraced the latest technologies to push the limits of manufacturing, production, marketing and wearability. Figure 1 shows an assortment of applications and properties that graphene can impart to textiles that aside from the obvious enhancements of mechanical and thermal properties, several secondary benefits such as antimicrobial, antistatic, ultraviolet (UV) and fire resistance can also be incorporated into textiles with clever engineering.

This white paper highlights Versarien's developments in the sportswear space, focused on taking our graphene prints and finishes for enhanced thermal and moisture management from the lab to market. It focuses on our collaborative work with a number of academic and commercial supply chain partners to realise optimised designs, performance and validated graphene enhanced garments.

Beyond enhancing the performance of textiles, the textile sector faces significantly larger challenges; the fashion industry is responsible for 10% of global carbon emissions – more than international flights and maritime shipping combined [2]. Further, according to a report [3], in 2017 the global fashion industry was estimated to have consumed 79 billion cubic metres of water, produced 1.7 billion tonnes of CO_2 emissions and 92 million tonnes of waste. Later, we discuss a few key areas where graphene and related materials and R&D activities that Versarien are pursuing, which could play a key role in reducing the impact of the textiles sector on our planet.

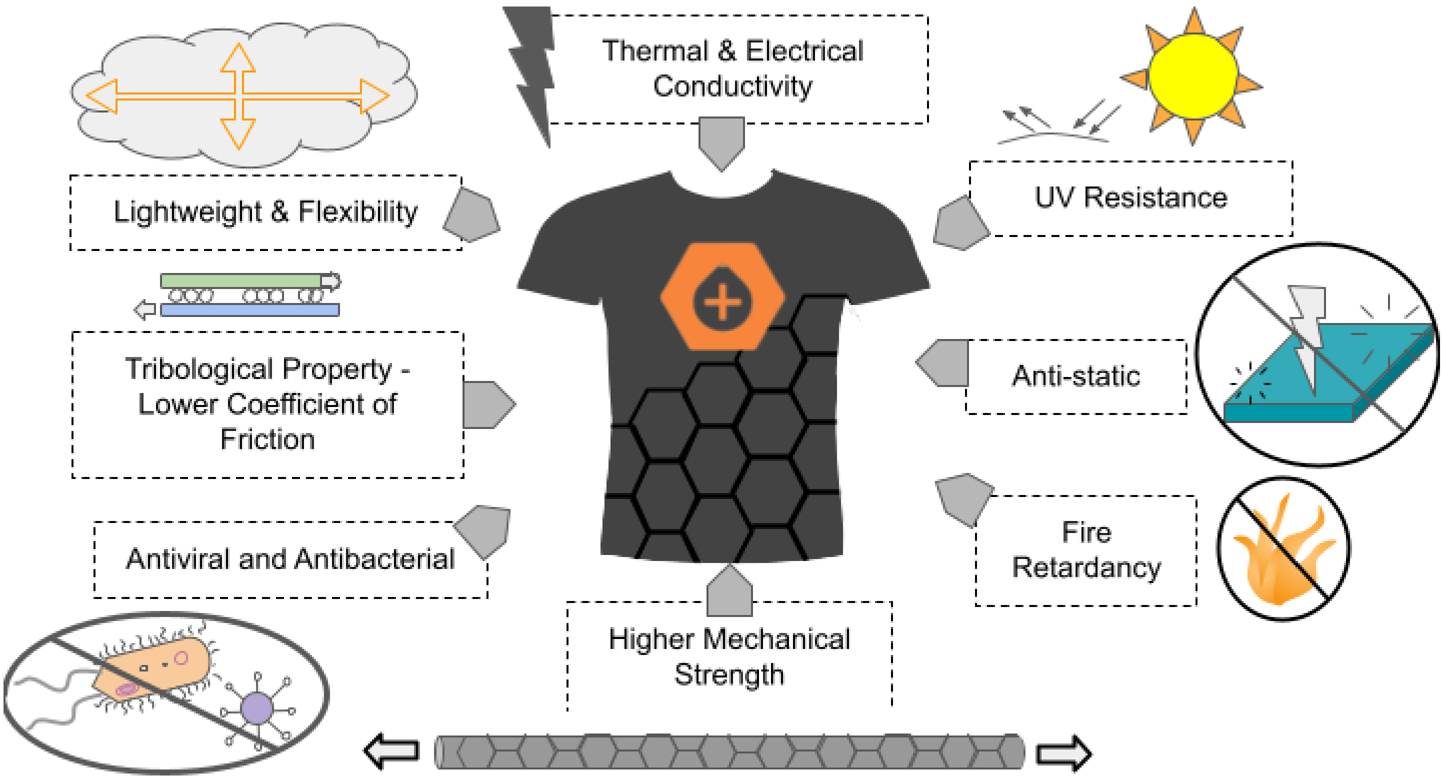


Fig. 1 Schematic representation of multifunctional properties of graphene-modified textiles.

Graphene Garments

CGC & InnovateUK

Versarien's exploits into the textile industry began in 2018 when Versarien subsidiary Cambridge Graphene Limited, a spin-out company from the Cambridge Graphene Centre (CGC) at University of Cambridge, won an InnovateUK funded project *"Upscaling novel microfluidisation for repeatable, low-cost creation of quality graphene ink"* [4] aimed to validate a pilot scale production of graphene ink from a proven novel, repeatable, microfluidisation process at lab-scale [5], utilising 3 key case studies to establish routes to market.

Fig. 2 Generation 2 activewear garments manufactured by MAS utilising **Graphene-Wear™**.

MAS

One of these case studies was a collaboration with Twinery – Innovations by MAS (part of MAS Holdings) in Sri Lanka, to understand the possible properties that graphene could impart to textiles. During this collaboration a water-based graphene formulation was developed which when dyed or printed, the graphene would coat and bind strongly to fabrics such that they were not removed by washing.

Generation 1 garments were produced using complete printed panels with graphene on the inside of activewear baselayers. Generation 2 garments looked to explore rotary screen printing and selectively printing graphene in areas where it would be most effective (e.g. chest, back, armpits). Designs were based on an interconnected network of graphene tracks to distribute heat and moisture (Figure 2).

RCA & GEIC

Formulation and rotary screen print trials were performed by Versarien at the **Graphene Engineering and Innovation Centre (GEIC)**, University of Manchester; the trials covered a range of parameters including the effect of fabric tension, print speeds, drying temperatures, screen mesh sizes, designs, and fabric compositions. Printing was performed using a Coatema Basecoater which has interchangeable print heads and was designed for pilot production before stepping up to full production. The printer was equipped with a convective air dryer and could print at speeds up to 20 m/min with a print resolution down to ~100 µm. Although not optimal for standard size textile printing, this trial helped in laying a further foundation of upscaling the printing of textile fabrics using **Graphene-Wear™** formulations at a commercial scale.

Versarien also began collaborating with the **Royal College of Art (RCA)**, London, with RCA academic and postgraduate staff assisting in the creation of several sportswear designs with basic design templates given by Versarien. Ultimately, RCA staff were given creative control over the designs to give striking appearance, whilst maintaining interconnectivity of the printed graphene network (Figure 3). This project involved the use of the **Graphene-Wear™** formulations and development of further formulations using different binder systems. The project expanded through three phases; Discovery, Selection and Production.

Fig. 3 Testing Versarien's ink formulations in different binder systems and printing on different substrates.

Graphene-Wear™ Textiles

Discovery: As well as practical elements, RCA and Versarien shared knowledge between the two in the form of seminars whereby Versarien gave an introduction to graphene [6] to RCA staff and undergraduate students, followed by RCA staff giving a textiles webinar to Versarien staff. In December 2021, Versarien staff and RCA graduates attended **Première Vision**, Paris, a trade show for textiles since 1973 that runs twice per year. Première Vision is widely considered in the industry as the heart of the international textile network, promoting the most innovative and unique designs, and emerging trends in the fashion industry. This event allowed us to source sports fabrics used in sportswear to test the performance of the **Graphene-Wear™** formulations on various fabrics for different sport applications from global suppliers. Fabrics were sourced in-line with specifications from brands interested in adopting Versarien's **Graphene-Wear™** and used as the basis of the design and print project with RCA.

Selection: RCA and Versarien selected an extensive range of fabrics and material composition types to test with our **Graphene-Wear™** formulations. These are shown in Table 1. Trials were predominantly performed on jersey fabrics, a soft stretchy, knit fabric that was originally made from wool. Today, jersey is also made from cotton, cotton blends, and synthetic fibres. Natural materials (cotton and wool), blends of natural, semi-synthetic (viscose) and synthetic materials (polyester, polyamide/nylon) with elastane, a synthetic fibre characterised by its extreme elasticity to add stretch to garments, as well as recycled synthetic materials (recycled polyester, recycled polyamide) have been tested.

Table 1 Fabric compositions used in the *selection* phase.

Type	Composition
Natural	100% Cotton
	100% Wool
Semi-Synthetic Blends	97% Viscose - 3% Elastane
	94% Cotton - 6% Elastane
Synthetics and Synthetic Blends	100% Polyester
	95% Polyester - 5% Elastane
	77% Polyester - 23% Elastane
	83% Polyamide - 17% Elastane
	82% - Polyamide - 18% Elastane
	77% Polyamide - 23% Elastane
Sustainable: Recycled Synthetics and Synthetic Blends	82% rPolyester - 18% Elastane
	47% rPolyamide - 31% Polyamide - 22% Elastane
	74% rPolyester - 26% Elastane
	92% Organic Cotton - 8% Degradable Elastane

Production: Five articles including upper and lower garments for different sports sectors were produced: football, rugby, tennis, golf and gym wear using further compositions to demonstrate the versatility of **Graphene-Wear™** across all sports (Table 2, Figure 4).

Table 2: Fabric compositions used in the *Production* phase.

Sport Garment Type	Composition
Rugby Top	90% Polyester - 10% Elastane
Leggings	92% Organic Cotton - 8% Degradable Elastane
Gym Top	82% rPolyester - 18% Elastane
Tennis Top	96% Polyester - 4% Elastane
Football Top	86% Polyamide - 14% Elastane

Fig. 4 Graphene-Wear™ formulations printed onto textiles that were fabricated into gym tops (upper) and tennis tops (lower).

Independent Fabric Testing

Throughout our print trials, we have undergone significant testing of graphene printed fabrics using Shirley® Technologies Limited. Shirley® is a wholly owned subsidiary of BTTG Ltd. BTTG Ltd. superseded the British Textile Technology Group, which was itself formed during the late 1980's from two globally renowned textile institutions; the Wool Industries Research Association (WIRA) established in 1918 and The Shirley Institute; the latter set up to support the cotton industry in 1919. Shirley® is accredited, as part of the BTTG Ltd. accreditation, by the United Kingdom Accreditation Service (UKAS), to the quality standard for testing laboratories EN ISO/IEC 17025.

Table 3 shows a set of tests that have been performed on **Graphene-Wear™** garments to date. Generation 1 garments were produced using complete printed panels with graphene on the inside of activewear baselayers (Figure 5). Testing was carried out by benchmarking the control garment without graphene. The results for Generation 1 garments confirmed stretch recovery with minimal dimensional changes, 10-25% improvement in air permeability, significantly improved wicking (50% and 100% depending on the direction of capillary action), 13-18% improvement in thermal transmittance and a comfort level that exceed the industry standard. Further testing has been performed on Generation 3 garments, as well as a subjective screening assessment for the presence of irritant substances, with criteria and methodologies based on Shirley® Technologies' experience, retail organisations' requirements and the OEKO-TEX® STANDARD 100 (described later). No presence of formaldehyde, oxidising or reducing agents, surfactant residues or dyestuff soluble in cold water was observed. Adding graphene to the base fabric does not make a significant difference to the skin irritation propensity of the fabric.

Fig. 5 Generation 1 activewear garments manufactured by MAS utilising **Graphene-Wear™**.

Table 3: Test methodologies used for graphene printed fabrics.

Test	Method	Description
Abrasion	**BS EN ISO 12947-2**	The surface of the fabric is abraded against a standard abradant fabric under defined conditions, until breakage of threads occurs
Stretch and recovery	**BS EN 14704-1**	A strip of fabric is cycled 5x to a prescribed load and the extension at load and unrecovered elongation is measured
Air permeability	**BS EN ISO 9237**	The resistance to air forced through the fabric under prescribed conditions
Water vapour permeability	**BS 7209**	The resistance to water vapour evaporating through the fabric under prescribed conditions
Water vapour resistance	**BS EN ISO 11092**	The resistance to simulated sweat evaporating through the fabric under prescribed conditions
Absorbency	**AATCC 79**	Time time taken for a drop of water placed onto the fabric to be completely absorbed
Wicking	**AATCC 197**	The rate of water flow up a vertical strip of fabric
Drying rate	**AATCC 199**	The time for a pre-wet fabric to be completely dried under prescribed conditions
Drying rate	**AATCC 201**	The time for a pre-wet fabric to be completely dried under prescribed conditions
Thermal transmittance	**BS 4745**	The resistance of fabric to radiant heat movement from warm to cold atmosphere
Presence of Irritants	**Shirley® Technologies**	Criteria and methodologies based on Shirley® Technologies' experience, retail organisations requirements and the OEKO-TEX® STANDARD 100

Independent Wearer Trials

An independent study of three sports garments including the **Graphene-Wear™** prototype garments were conducted in 2021 (Figure 6). The study was supervised by Professor Athanassios Bissas of the School of Sport and Exercise at University of Gloucestershire. Professor Bissas is currently deputy chair of the Biomechanics Division of The British Association of Sport and Exercise Sciences and is well respected for contributing to publications in over 50 peer reviewed papers and textbooks. The experimental procedures were approved prior to deployment by University of Gloucestershire Research Ethics Committee.

The aim of the study was to explore the thermal and moisture management properties of three different semi-fitted, long-sleeved, baselayer tops when worn during exercise, and to assess the wearers' perception and comfort levels whilst wearing the garments. The three garments tested were the **Graphene-Wear™** (**G-W**) generation 3 garment (Figure 7), a garment from a high market share brand marketed to have moisture management properties (G-2) and a garment from a brand with high market share marketed to have moisture and thermal management properties (G-3). In terms of fabric composition, **G-W** and G-2 are closely matched (92% Polyester - 8% Elastane), while G-3 is ~50% Polyamide - 50% Polyester.

Fig. 6 Subjects performing sub-maximal effort treadmill runs at University of Gloucestershire wearing **Graphene-Wear™** baselayers.

Fig. 7 Generation 3 activewear garments manufactured by MAS utilising **Graphene-Wear™** used in University of Gloucestershire wearer trials.

As study subjects, 11 aerobically trained male athletes of an intermediate to elite standard of running (average $\dot{V}O_2$ max: 53.00 $mL.kg^{-1}.min^{-1}$) were selected. In a random order, subjects performed a sub-maximal effort treadmill run (70% $\dot{V}O_2$ max) for a set duration of 50 minutes whilst wearing one of the trial garments. This was repeated for each garment after a time interval of at least 48 hours. Body mass, garment mass, urine osmolality levels, heart rate, blood samples and internal core temperature were collected/measured every 10 minutes. Finally, after each test, an interview developed by Raccuglia, Holder and Havenith [7] took place to record wetness perception, thermal sensation and thermal comfort.

Thermal Management

Heat is created as a byproduct of exercise and is expelled via increased blood flow and sweating, with any excess heat being stored [8]. Maintaining optimal core temperature is key to many bodily functions including metabolic rate and tissue mechanics and has been widely researched. Significant increases in core temperature are accompanied by an increase in cardiovascular strain, fatigue, and performance decline [9]. It has therefore been a competitive market space for sports apparel brands to offer garments that prevent a shift in core temperature above or below an optimal level.

Subject core temperature was the key measurement in establishing each garment's thermal management capabilities. As shown in Figure 8, G-3 recorded the lowest pre-run core temperature reading of 36.65°C and rose to 38.24°C. **G-W** recorded 36.83°C to 38.10°C (the lowest increase in temperature). G-2 recorded the hottest pre and post-run temperatures of 36.92°C and 38.34°C, respectively. The only observed decrease in core temperature across all garments was observed with **G-W** between 40-50 minutes.

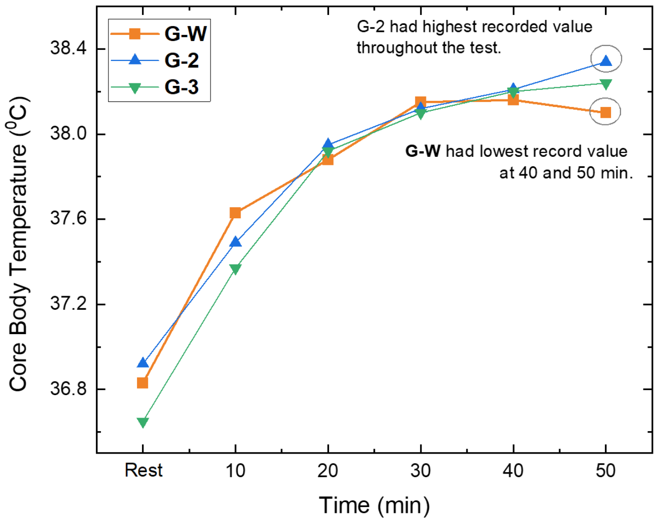


Fig. 8 Subject core body temperature at rest and during the course of the 50 minute test.

Moisture Management

Subjects with an average mass of ~75 kg reduced in mass through sweat loss G-3 (~1.66 %), **G-W** (1.82 %), G-2 (1.90%). G-3 and **G-W** showed similar % change in garment mass (+93% and +95%, respectively) with G-3 higher (+108%). Through the constraints of this study, the exact percentage of sweat expelled from the body via evaporation and skin run-off cannot be calculated, however, it can be indirectly estimated that **G-W** absorbed the lowest % of sweat created at 11.7%, G-2 at 12.3% and G-3 at 12.8%. With the assumption that skin run-off was approximately equal, it could be concluded that **G-W** promotes better evaporative cooling than G-2 and G-3.

Just as with thermal management, more in-depth studies that focus on higher resolutions, frame rates and increased datasets will allow a broader understanding of the moisture management capabilities of garments and their technologies.

Perception

The type and quantity of physical activity performed by recreational, amateur or elite athletes has been observed to be influenced by the level of comfort achievable with the surrounding environment [10]. The haptic perception of heat and wetness while wearing clothing represents one of the most critical factors contributing to thermal and sensorial discomfort during exercise [11–13].

Subject interviews pre, during and post-run included queries about the garments' physical appearance, whether they aided performance, influenced their run intensity, style, speed and recovery as well as whether they felt comfortable, etc. There was an acceptable level of thermal sensation and comfort across all the garments, with no distinguishing differences between garments, although not all participants agreed with each other, which is accounted for by personal preferences. On a wetness perception scale, **G-W** was perceived to be the wettest, followed by G-3 and G-2 as the driest. These perceptions do not support the laboratory and qualitative data; brand awareness is potentially playing an important role in the perceived credibility of a garment. Research has shown that if a brand is well known, highly endorsed and has a loyal customer base, it can have an effect on how the subject perceives the garment's technology will perform and how comfortable it is whilst being worn [14].

Overall Performance

Although the sample size is small (11), overall, **Graphene-Wear™** competes well with an existing high market share garment (G-3), and performed better than an equivalent fabric composition market leading garment (G-2) in both thermal and moisture management (Table 4).

Table 4: Overall performance rankings of the tested garments.

Garment	Thermal Performance	Moisture Performance	Perception Ranking	Overall Performance
G-W	1	=1	3	=1
G-2	3	3	1	3
G-3	2	=1	2	=1

Commercial Traction

Following fabric testing results at the lab scale highlighting some impressive features of the **Graphene-Wear™** garments, in November 2019 Versarien and MAS Innovation signed a commercial partnership agreement. The agreement followed a letter of intent between the parties, which set out their intent to enter into a formal commercial partnership. This agreement specified the terms under which the parties would secure commercial orders for garments developed using Versarien's proprietary **Graphene-Wear™** formulations and allowed both parties to finalise additional contractual terms with third party brands.

Although the COVID-19 pandemic had a massive impact on the textile sector, in an effort to build on the **Graphene-Wear™** technology and understand the full extent to what graphene could offer, aided by MAS, Versarien optimised the ink formulation, further scaled up the graphene ink production processes, optimised designs and printing procedures and have undergone significant lab and wearer trials, funded through our Innovate UK G-SCALE program [15]. Generation 3 garments were then produced by MAS for distribution to brands, agents and for further lab and wearer trials (discussed previously). Versarien also worked with other partners to support the fight against COVID-19 by working with partners to bring graphene enhanced personal protective equipment (PPE) to market in the UK and Europe with FFP2 RD facemasks for adults and face coverings for children.

Superdry

In Q4 2021, Versarien announced a collaboration agreement with fellow Gloucestershire firm and global fashion brand Superdry, to develop enhanced textiles, garments and future products using Versarien's **Graphene-Wear™** technologies [16]. Versarien will work closely with the research and development team with the aim to accelerate Superdry's innovation platform and create ownable technologies, enabling the creation of products unlike anything else on the market. The collaboration, encompassing multiple projects across different categories, will initially focus on improving the performance of sports clothing by utilising graphene's thermal and moisture management properties. Another area of focus will be to utilise the mechanical strength of graphene to improve the functionality of products. An example of this would be creating garments that will last longer with little fibre failure, increasing the number of wears and washes per garment.

Superdry has a strong focus on sustainability and environmental impact and has stated the goal to become the most sustainable listed global fashion brand and become Net Zero by 2030. Versarien will be supporting these goals with the numerous advantages that graphene can offer to the many stages of the supply chain. Both brands are excited for the future ahead and the possibilities that will be created.

Neill Ricketts (Versarien CEO), left & Julian Dunkerton (Superdry CEO), right.

Textile Industry Databases & Standards

Due to the interdependence of international markets, textile and apparel supply chains have become more globalised as they become even more connected to - and within - developing countries [17]. Historically, the textiles industry has been associated with many issues such as environmentally harmful processing, child labour, animal welfare, social compliance and health and safety issues. Today, there are a number of certifications that can be sought to ensure that harmful chemicals are not used in the manufacture of textile products and public platforms exist to give transparency regarding apparel and footwear supply chains.

In the textiles supply chain, Versarien is classed as a formulator; **Graphene-Wear™** printing formulations can be categorised as "Textile auxiliaries for dyeing and printing", or as a "functional constituent/ingredient". There are a range of textile industry standards and certificates that cover ecological and toxicological concerns with key databases and standards highlighted in this section.

Zero Discharge of Hazardous Chemicals (ZDHC)

The Zero Discharge of Hazardous Chemicals (ZDHC) programme was initiated by six apparel manufacturers in 2011. ZDHC is dedicated to eliminating hazardous chemicals and implementing sustainable chemicals in the leather, textile, and synthetics sectors. The ZDHC Manufacturing Restricted Substances List (MRSL) sets guidelines as to which chemical substances are forbidden for application in textile finishing, or for use in clothing and footwear. The ZDHC programme is a multi-stakeholder group that includes brands, value chain affiliates, and associates that work collaboratively to implement responsible chemical management practices. The ZDHC Chemical Gateway Database was established in June 2017 and Versarien are the first graphene manufacturer to sign up with **Graphene-Wear™**, **Graphink™** formulations and **Nanene™** powder products produced in accordance to the MRSL as listed on the ZDHC Gateway system (**ZDHC AID: A201HB47**).

OEKO-TEX®

OEKO-TEX® offers companies in the textile and leather industry various certificates and services with the aim of verifying the safety of products and their production processes for health and the environment. STANDARD 100 by OEKO-TEX® was introduced in 1992, independently testing the quality of textile goods and all production stages. Every component of an article, i.e. every thread, button and other accessories, are tested for harmful substances. ECO PASSPORT by OEKO-TEX® is an independent certification system for chemicals, colourants and auxiliaries used in the textile and leather industry. Each individual ingredient in the chemical product is analysed to ensure it meets the statutory requirements and that it is not harmful to human health, essential to give credibility to both brands and manufacturers. Once per year, OEKO-TEX® updates the banned substances and limit values and expands them to include new scientific findings or statutory requirements.

bluesign®

The bluesign® label is presented by the Swiss company bluesign technologies ag. The bluesign® system aims to ensure sustainable textile production focussing on avoiding dangerous, environmentally hazardous substances, and ensuring the eco-friendliness of all production processes in the textile chain including the technologies applied and raw materials used. Social aspects and occupational safety in the production facilities of the bluesign® system partners are also taken into account in the certification process.

Global Organic Textile Standard (GOTS)

The Global Organic Textile Standard (GOTS) provides guidelines for the ecological and socially responsible manufacturing of textiles. It is internationally recognised as the leading global standard for processing textile goods which contain at least 70% organically grown natural fibres. The quality of GOTS certified textiles is ensured through independent controls of the entire supply chain, from the extraction of the raw fibres to the labelling of the completed textile products.

GOTS defines groups of substances which are not permissible, or only partially permissible, and thus not acceptable for use in the manufacturing process. Unfortunately, nanoparticles defined as materials with at least one dimension below <100 nm are prohibited under GOTS; further ecological, toxicological and exposure route data regarding graphene, for example, constantly being updated as part of necessary REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals), may provide sufficient evidence to overturn this widespread banning.

Open Apparel Registry (OAR)

The Open Apparel Registry (OAR) exists to improve human rights and environmental conditions in and around factories and facilities by opening up supply chain data contributed to, and used by organisations all over the world. Versarien Graphene Limited's Longhope, Gloucestershire, UK facility is listed on the OAR (**OAR ID: GB2022013E69BZT**).

The Graphinks™ used in our **Graphene-Wear™** formulations are water-based. The graphene is dispersed using a plant-based, palm oil-free stabiliser.

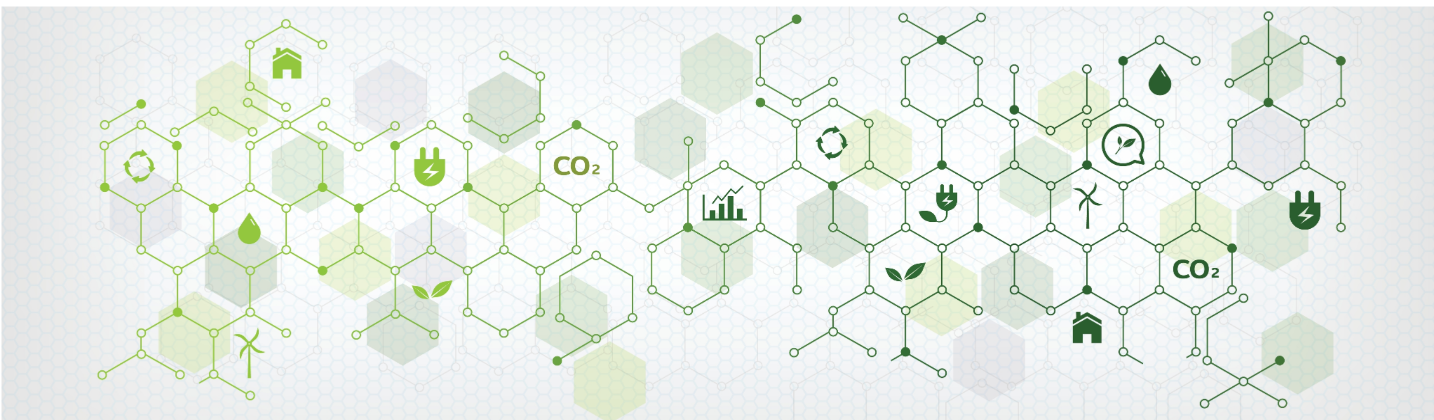
Summary & Future Outlook

In this white paper, we have highlighted the significant progress made in developing and proving **Graphene-Wear™** technology in the lab and in real-life environments. The purpose of wearer trials was to establish how the thermal and moisture management of **Graphene-Wear™** baselayers compared to market leading garments as well as perceived awareness and comfort. Although the sample size was small (11), overall, **Graphene-Wear™** competed well with an existing high market share garment, and outperformed a market leading garment in both thermal and moisture management with an equivalent fabric composition. Versarien will continue to work closely with the team at University of Gloucestershire in developing further studies to explore additional controlled and uncontrolled environments including both genders and further garment types. **Graphene-Wear™** formulations have been developed to be compatible with traditional dyeing and high-throughput rotary printing techniques, although more sophisticated Direct to Garment (DTG) digital printing is an alternative option for future investigation.

Beyond enhancing the performance of textiles, sustainability of the textile sector and the impact on climate change is currently at the forefront of the political agenda; **Textiles 2030** is a new expert-led initiative, harnessing the knowledge and expertise of UK leaders in sustainability to accelerate the whole fashion and textiles industry's move towards circularity and system change in the UK. Targets include reducing aggregate greenhouse gas footprint of products by 50% and reducing the aggregate water footprint of products by 30% [18]. As an innovative multi-functional material, graphene can play a key role in helping to meet such future targets.

There is a rapidly growing interest in replacing synthetic fibres with natural and bio-based polymers, however, these alternatives often suffer from poor mechanical properties limiting their use in wider applications. In such situations graphene has also been shown to be able to re-engineer natural fibres to perform like synthetic materials [19]. In a similar fashion, graphene can assist in the use of recycled materials for textile production. As the use of polyester grows, especially in the sportswear sector, there is an opportunity to increase the use of recycled polyester to help minimise carbon emissions. The primary disadvantage is that the resulting recycled material is often weaker and less durable than the virgin material. Adding graphene to recycled plastics can produce a stronger, longer-lasting material, providing a way to further reuse our waste products, preventing them from going to landfills. Where re-use displaces a sale of a new garment, the effects on the environment from fibre extraction and processing are also avoided [20]. Synthetic fabrics made from recycled synthetic yarns use 35-50% less energy and generate 79% fewer carbon emissions than using virgin synthetics [21]. With recycled synthetic fibres such as recycled polyesters (rPET) already making their way into markets, there is a scope of graphene to add further functionalities to these fibres and make them usable in a wider range of fashion, technical textiles and accessories.

Working in collaboration with industrial partners, Versarien has already developed a variety of polymer compounds and masterbatches that feature different types of virgin and recycled polymers, along with different weight loadings of Versarien's graphene, all under the company's graphene-enhanced polymer range, **Polygrene™**. These can be used in industrial extrusion and spun into fibres/filaments, which can provide a further element of performance improvement in creating stronger, more durable yarns and could help to alleviate environmental issues such as microfibre shedding; ~0.5 million tonnes of microfibres end up in our oceans each year, accounting for 35% of primary microplastics released into the environment [22]. Versarien are members of the **Bio-Based and Biodegradable Industries Association (BBIA)** and have performed trials on biodegradable materials containing up to 5% graphene loading (**Nanene™** was used) that have passed ecotoxicity tests in line with standards including **EN 13432:2000** *Requirements for packaging recoverable through composting and biodegradation - Test scheme and evaluation criteria for the final acceptance of packaging*, **ASTM D6400:2019** *Standard Specification for Labelling of Plastics Designed to be Aerobically Composted in Municipal or Industrial Facilities* and **ISO 17088:2012** *Specifications for compostable plastics*. Testing was performed by OWS, Belgium. Ultimately, if a material is degradable, relatively high amounts of Verarien's graphene can be added without compromising its ability to pass relevant global compostability standards.



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