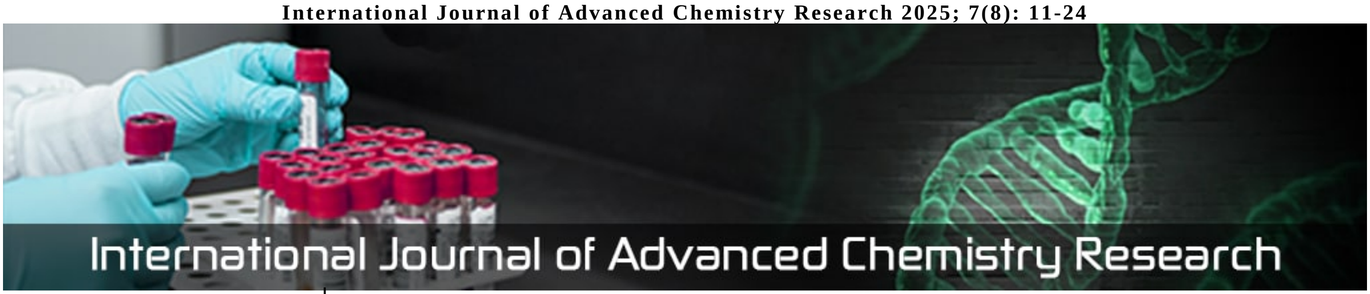
International Journal of Advanced Chemistry Research 2025; 7(8): 11-24



ISSN Print: 2664-6781
ISSN Online: 2664-679X
NAAS Rating (2025): 4.77
IJACR 2025; 7(8): 11-24
www.chemistryjournals.net
Received: 12-06-2025
Accepted: 14-07-2025

Shalini Rukhaya
Assistant Professor, Department of Apparel and Textile Science, I.C. College of Community Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, India

Nisha Arya
Associate Professor, Department of Apparel and Textile Science, I.C. College of Community Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, India

Pratibha
Research Scholar, Department of Apparel and Textile Science, I.C. College of Community Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, India

Corresponding Author:
Shalini Rukhaya
Assistant Professor, Department of Apparel and Textile Science, I.C. College of Community Science, Chaudhary Charan Singh Haryana Agricultural University, Hisar, Haryana, India

Auxetics: An innovative approach to technical textiles

Shalini Rukhaya, Nisha Arya and Pratibha

DOI: https://www.doi.org/10.33545/26646781.2025.v7.i8a.304

Abstract
The textile and clothing market represents one of the key sectors in global trade and product production. Due to technological advancements, rising competition, and shifts in society, the use of textiles and clothing is expanding greatly across various different sectors. Studies are being conducted to create technical textiles with distinctive characteristics by modifying their structure and surface at various levels to enhance their functionality. One notable initiative in the area of technical textiles is the auxetic fabrics. In recent times, the application of textile technology to create auxetic materials has garnered significant interest. Auxetic textiles are materials that exhibit a negative Poisson's ratio; unlike traditional textile materials, when they are elongated in the longitudinal direction, they experience a slight increase in the transversal direction. Auxetic materials possess a range of remarkable characteristics, including fracture toughness, resistance to indentation, synclastic curvature, impact resistance, and variations in porosity and permeability. Because of their diverse properties, auxetic materials find applications in various fields such as healthcare, architecture, civil engineering, advanced equipment, explosive protection, filters, and more. They are likewise utilized in the production of functional apparel, healthcare, athletic, and safety garments. Despite numerous suggested uses, actual implementations of auxetic materials remain restricted to the initial phase. Future efforts should focus more on developing new auxetic materials with practical applications for mass commercialization.

Keywords: Auxetic textiles, negative Poisson's ratio, technical textiles, impact resistance, functional apparel, textile innovation, advanced materials

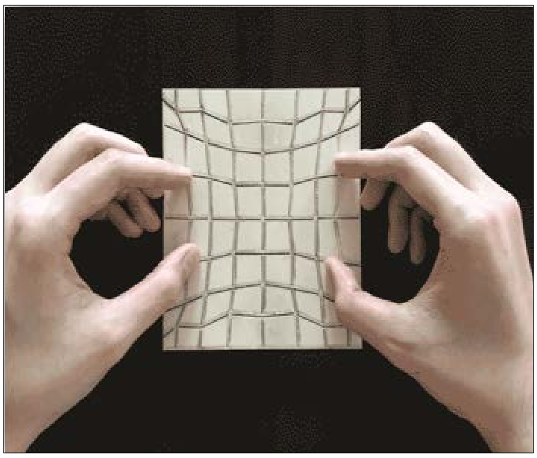
Introduction
The textile and apparel industry is a major segment in global trade and product production. Traditionally, the textile sector is associated with the creation of fibres, yarns, fabrics, and textile products. In the realm of technology advancement, rising market competition and societal transformations demand new solutions, leading to a broader application of textiles. The emphasis on keys for innovations in technical textiles arises from multidisciplinary research, attributed to distinctive textile characteristics like lightweight nature, flexibility, dimensional variability, and the potential to obtain specific properties via structural and surface alterations at various levels (Darja *et al*., 2014) [7]. Numerous instances demonstrate successful attempts to enhance the physical and chemical attributes of technical textiles and broaden their functionality. An illustration in the realm of technical textiles encompasses the auxetic textiles. In recent times, the research on auxetic materials derived from textile structures has garnered significant interest. Auxetic fabrics are remarkable materials that expand in fibre diameter when stretched, in contrast to standard textiles that tend to flatten. This characteristic arises from its Negative Poisson's Ratio (Julia, 2017) [15].

$$\nu = -\frac{\text{Strain in direction of load}}{\text{Strain at right angle to load}}$$

$$\nu = -\frac{\varepsilon_{lateral}}{\varepsilon_{axial}}$$

Poisson's Ratio

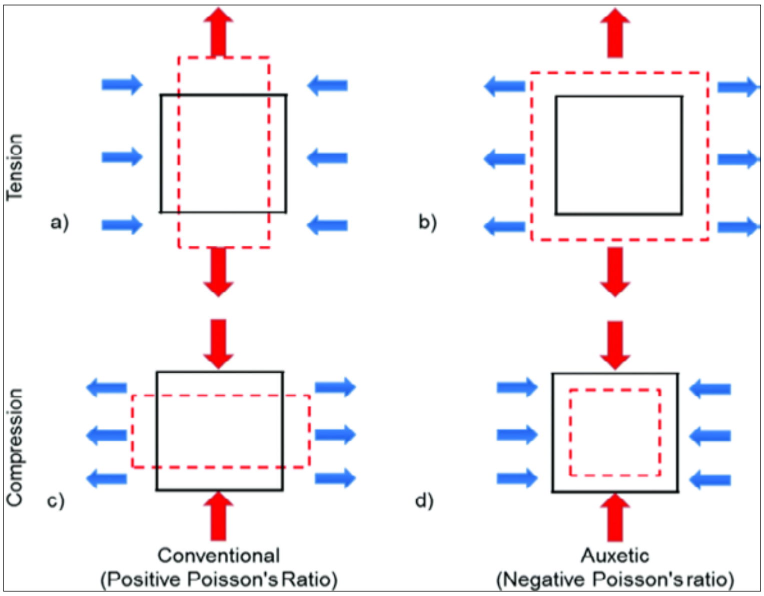
When a material is pulled, it not only elongates in the direction of the pull but also becomes narrower in its cross-section. In this situation, the material's response to deformation is determined by a key mechanical property known as Poisson's ratio (V). The majority of the materials exhibit a favorable V (0.0-0.5). However, due to the counterintuitive nature of auxetic materials, they expand laterally when they are stretched (Negative V).



In 1987, Lakes initially documented an auxetic foam, specifically a polyurethane foam with a re-entrant structure that could be readily produced through a tri-compression and heating method (Poisson's ratio of -0.7). His research demonstrated that auxetic materials could be produced artificially as well. Following that, additional scientists started to investigate auxetic materials. So far, numerous auxetic materials have been discovered in nature or created artificially. Evans K of the University of Exeter named these new categories of materials auxetics. The word auxetic comes from the Greek term "*auxetikos*," translating to "that which tends to grow" (Webb, 2016 [34] and Srivastava *et al*., 2020) [30].

Conventional vs. Auxetic Material

When traditional materials are pull along their length (longitudinal section), they become thinner in their width (cross section), and when they are compressed in their length, they become thicker in their width. The opposite applies to auxetic materials, meaning that when they are pulled in their length, they increase in thickness in both the length and width, and when they are compressed in length, they reduce in thickness in both directions (Sayed and Samarth, 2019) [27].

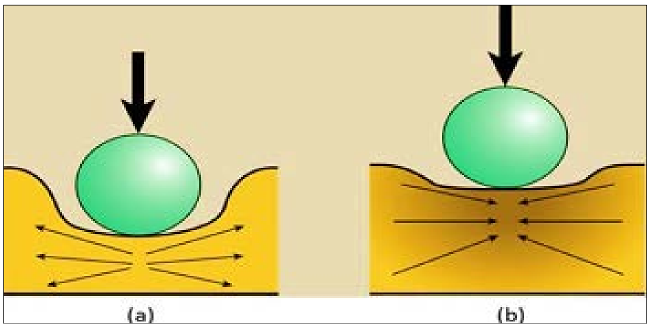


Auxetic materials and structures are gaining significant popularity within the scientific community, particularly among materials engineers and textile specialists. This is due to their remarkable characteristics, including rigidity modulus, fracture toughness, shear moduli, resistance to indentation hardness, synclastic curvature, impact toughness, and variations in porosity and permeability when under pressure. Because of their diverse properties, auxetic materials can be utilized in multiple fields such as medicine, architecture, civil engineering, athletic apparel, high-performance gear, protection from explosives, insulation, filters, and more. They are additionally utilized in the production of functional apparel, healthcare, and safety clothing (Jiang *et al*., 2016) [14].

Properties of auxetic textiles

1. Indentation Resistance

When a traditional material experiences indentation, the force/load exerted compresses the material. The material subsequently offsets the pressure by dispersing perpendicular to and away from the direction of the applied force/load. Auxetic materials, when subjected to indentation, shrink, forming a region of denser materials that exhibit increased resistance to indentation. The auxetic UHMWPE demonstrated 2.5 times the resistance to indentation compared to traditional UHMWPE. The improved indentation resistance has likewise been observed in other auxetics, such as auxetic fibre-reinforced composites (Grima *et al*., 2011) [12].



a. Non-auxetic and b. Auxetic Material

2. Synclastic Curvature

The synclastic behaviour of a material or body refers to its capacity to deform into a dome shape when it is bent. Typically, when a material is curved, it experiences both compressive and tensile stress, resulting in its deformation. The traditional material that takes on a saddle shape when curved demonstrates an anti-clastic curvature. Auxetic materials, when bent, expand outwardly and shrink inwardly. The expansion and contraction present in the auxetic material result in its transformation into a dome shape (Duncun *et al*., 2018) [9].

a) Saddle shape (conventional) b) Dome shape (auxetic)

3. Fracture Toughness and Crack Resistance

Materials with a negative Poisson's ratio exhibit greater fracture resistance compared to conventional materials. They also exhibit low crack growth, requiring additional energy to enlarge them. Thus, these types of materials exhibit a fragile fracture.

Shan *et al*. (2015) [29] examined the durability of auxetic foams based on the permanent volumetric compression ratio. The strength of auxetic foams was enhanced by 80%, 130%, and 160% for permanent volumetric compression ratios of 2.0, 2.5, and 3.0, respectively, in comparison to conventional foams.

4. High Shear Stiffness

Shear modulus (G) is a characteristic evaluated to ascertain the distortion that happens when a force is exerted parallel to one side of an object while the opposite side remains stationary. A large shear modulus indicates that the material is stiff and possesses high resistance to shear. Therefore, shear modulus is a crucial element to consider when planning and producing any structure. In isotropic auxetic materials, shear resistance is anticipated to be more advantageous compared to non-auxetic materials (Moroney *et al*., 2018) [22].

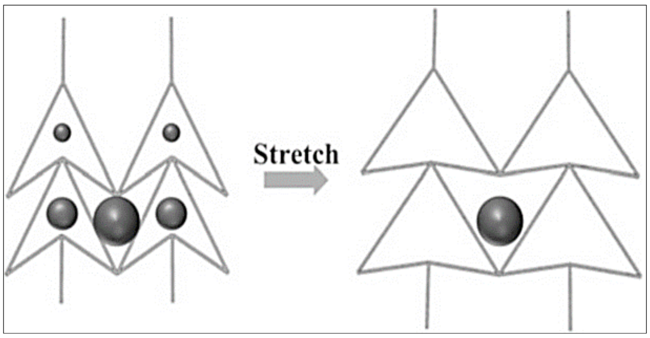
5. High Energy Absorption

Auxetic materials possess better energy absorption characteristics. The cyclic compression tests on auxetic foams revealed that the damping capacity of auxetic foams was ten times greater than that of the original conventional foams utilized to create the auxetic foams. The capacity to take in sound relies on the pore size of an auxetic foam, which is optimal for NPR foams featuring smaller pores at frequencies over 630 Hz. Furthermore, NPR covered foams demonstrate superior acoustic absorption properties than NPR uncovered foams within the frequency range of 250 to 1000 Hz. Sound absorption capacity and crashworthiness of auxetic materials were also noticed to be increased as compared to the conventional materials (Darijo, 2017) [6].

Alderson *et al.*, 2010 [1] experimentally showed that the maximum ultrasonic attenuation coefficient of auxetic UHMWPE was 1.5 times greater than that of nonauxetic microporous UHMWPE and 3 times greater than conventionally processed foams. Moreover, auxetic foams demonstrate remarkable resilience during dynamic impact loading, a characteristic that is not observed in traditional foams. In addition, Baker, 2015 conducted experiments on the sound absorption characteristics of an auxetic foam treated with magnetorheological (MR) fluid compared to traditional foam. The auxetic PU foam demonstrated improved crashworthiness features and greater sound absorption capabilities (particularly at low frequencies). A cyclic compression test on auxetic foam shows that the damping ability of auxetic foams was 10 times greater than that of the original conventional foams used in creating the auxetic foams.

6. Variable Permeability

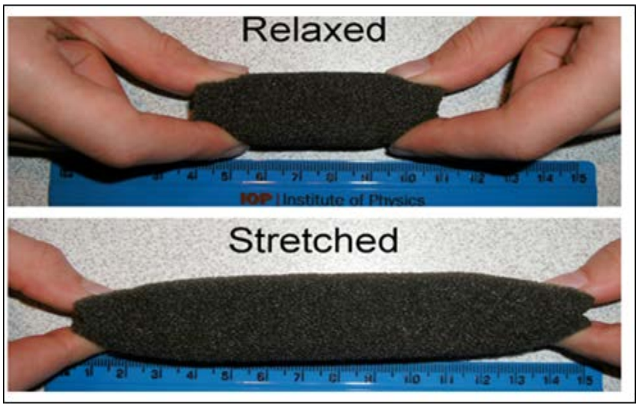
Auxetic materials have been shown to possess a distinctive pore-opening that allows them to provide enhanced filtration efficiency across both macro-scale and nano-scale filter performance. When auxetic materials are stretched, their pores expand in both the axial and perpendicular directions. These distinct features can assist in mitigating the decrease in filtration efficiency and heightened pressure across the filter caused by blocked pores. A triangular re-entrant design enhances permeability by modifying the pore size as each unit cell expands in multiple directions.



A diagram of variable permeability in a triangular re-entrant structure

7. Shape Memory Auxetics

Shape memory refers to a material's ability, when experiencing plastic or semi-plastic deformation, to recall and revert to its original shape and size upon receiving a particular thermal stimulus. Research in this area demonstrated that auxetic foams can be converted back to standard foams multiple times without any degradation of mechanical properties (Anonymous, 2020) [3, 4, 5].



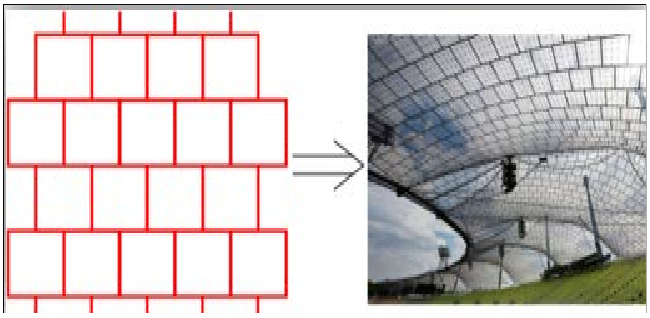
Other Auxetic Properties

The enhanced fracture toughness and hardness of auxetic materials propose that these materials could exhibit superior tribological properties compared to traditional materials. This is supported by the characteristics that minimize abrasive wear in auxetic materials. This potential was validated in study by Uzun, 2010, which showed that auxetic weft knitted fabric demonstrated a 15-35% increase in abrasive wear resistance compared to traditional polypropylene knitted fabrics.

Applications of auxetic materials

Auxetic Architecture

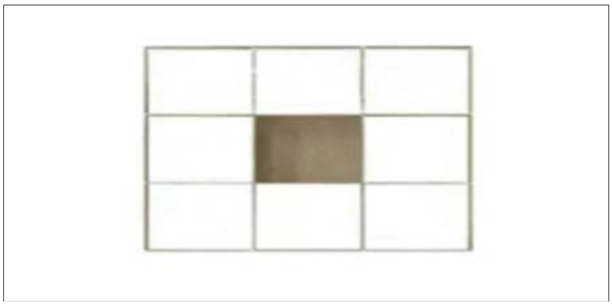
A recent movement has emerged towards auxetic architecture, where these materials, due to their structural versatility, aesthetic appeal, and various other factors; are utilized in structures like the Munich 1972 Olympic Park roof, reminiscent of the open re-entrant structure. In the future, these domes may be built using auxetic structures to minimize the time, resources, and materials needed for constructing these remarkable structures (Dudek *et al*., 2017) [8].



(Left) the opened re-entrant structure defined above along with (right) the Munich 1972 Olympic Park roof

Auxetic Furniture

Auxetic furniture has also fascinated attention because of its functionality and design. A better way to define this furniture would be to call it "furniture that you never get bored of" as it can be alter according to requirement. A table that can be made larger by only pulling it or shelves that can be adjusted depending on what is to be showed.



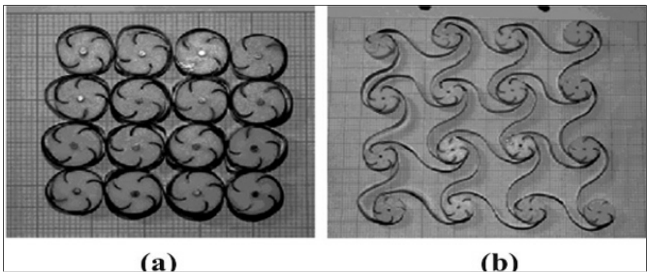
Shelves incorporating the rotating squares auxetic mechanism

By utilizing auxetic foams, which are foams altered through heat and pressure processes, the negative Poisson's ratio can be attributed to the presence of rotating rigid units and/or re-entrant mechanisms at the microscale. These elements in seating may boost comfort by strategically positioning various foams, thereby enhancing back support and promoting better posture, crucial in today's digital era.

Santulli and Langella, 2016 [25] applied auxetic materials in various design items, such as chairs, bags, seat belts, etc., as auxetics have gained attention in engineering, especially when a support system rather than a strong flexure of a cellular, thus lightweight and comfortable substance, is needed.

Aerospace

Auxetic materials can be utilized in creating a chiral honeycomb deployable antenna for deep space missions, leveraging their shape-memory characteristics. This antenna is compacted during transport due to the restricted space for rocket launchers. When in space, the shape memory structure harnesses solar thermal energy to return to its initial size (Shajoo *et al*., 2021) [28].

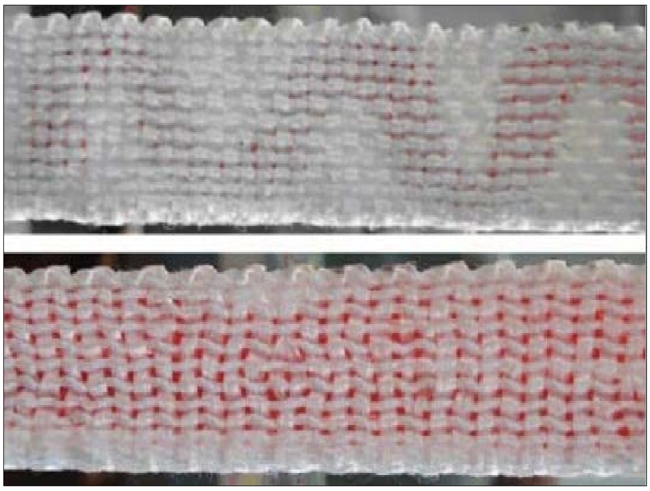


(a) Folded and (b) unfolded auxetic cellular antenna

Auxetics in Industrial Textiles

- **Colour-change Cargo Straps and Fabrics**

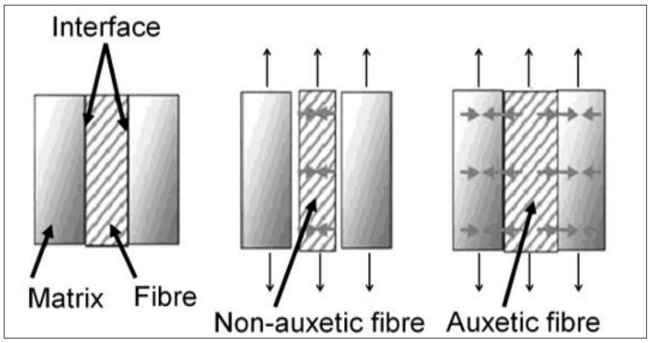
Cargo straps must be adjusted properly, as improper tension could lead to hazardous and costly consequences. To prevent these issues, auxetic are creating a webbing that alters its colour when tightened; it shows one colour at the ideal tension and changes to a different one beyond that point. A fabric that changes colour is also being created where an auxetic mesh is provided with a properly-coloured backing material. Upon being pulled, the openings reveal the underlying colour (Saxena *et al*., 2016) [26].



Sample of Change-colour Fabric: (a) stress-free and (b) under stress

- **Composite and Masonry Reinforcement Fibres**

In the textile sector, auxetic materials including auxetic filaments, auxetic yarns, and auxetic fabrics have broader uses. All of them can serve as reinforcements in composite materials, effectively improving various properties. Auxetic fibre reinforcements additionally improve the failure characteristics of composites. Fibre pullout constitutes a significant failure mode in composites. A unidirectional composite subjected to tension will experience lateral shrinkage in both the matrix and fibre materials, resulting in failure at the fibre/matrix boundary. On the other hand, auxetic fibres enable the potential to preserve the interface through precise alignment of the Poisson's ratios of the matrix and the fibre (Umut *et al*., 2018) [32].



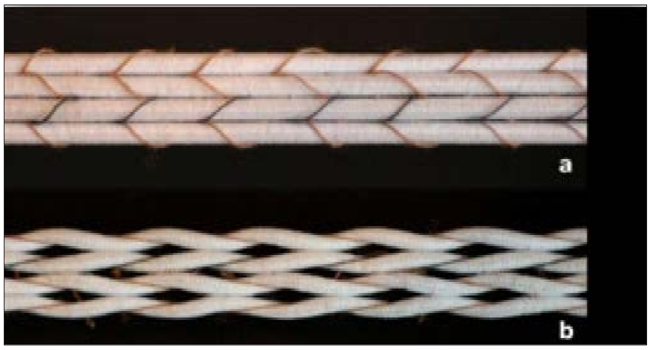
- **Fibre pullout in composites**

Predicted anchoring influence provided by fibre with negative Poisson ratio when under tensile load. The fibre to expand instead of contract; maintaining interfacial contact for longer due to auxetic effect.

Liaqat enhanced the impact resistance of the composite by modifying the thickness of the woven structure across the four layers, which served as reinforcement. The modified four layers within the thickness woven structure exhibited auxetic properties in both warp and weft directions, displaying reduced penetration resistance in contrast to the standard sample. The non-auxetic woven structures with four layers through their thickness and modified auxetic woven structures with four layers were utilized as reinforcements to create composites for comparing impact resistance. The findings indicated that the impact resistance of the auxetic composite was 6.7% higher than that of the non-auxetic composite. The higher impact resistance was attributed to the auxetic properties of the modified four-layer, three-dimensional woven design.

- **Filters**

Auxetic foam and honeycomb structures can be utilized to create intelligent filters, where the size of the pores can be adjusted by changing the applied load, thereby regulating the size of particles permitted to pass through the filter, which also facilitates the simple cleaning of clogged filters. These advantages depend on the pores expanding both parallel and perpendicular to the direction of a tensile force exerted on an auxetic filter.



Auxetic Filters: (a) stress-free; (b) under stress

Greaves *et al*., 2011 [11] propose that auxetic materials could potentially be used as nanofilters at the nanoscale. Nanofiltration involves filtration at the atomic or molecular scale using filtration systems composed of atomic frameworks. This represents a proposed use of nanoscale auxetic porous networks like reflexyne, which can alter their pore size in an auxetic manner, meaning that stress application allows for the adjustment of pore dimensions.

- **Self-locking Stitching Threads**

A primary function of securing threads like shoelaces, medical sutures, or stitching threads is to stop undesirable movements of textiles. In each of these cases, two problems exist where the auxetic effect may be advantageous. First, there is the issue of thread slipping, and second, there is the tendency for the fastening knot to unfasten. The thread becoming thinner as it is pulled increases the likelihood of failure. If the thread is auxetic, it would stretch under tension and securely fix itself in position, stopping both knot and stitch from slipping (Lee *et al*., 2015) [18].

- **Fasteners and Rivets**

Since auxetic materials widen laterally when stretched, they would be perfect for creating fasteners and rivets. The auxetic fastener's insertion is eased by the lateral contraction during compression, whereas its removal is impeded because the fastener expands and locks itself more securely in the hole under tension. It can be seen that the expansion resulting from the removal needed a larger load than that required for the fastener insertion.

- **Rope or fishnet**

Those crafted from auxetic fibres will possess improved strength characteristics. Apart from the strength improvements, auxetic fibres also demonstrate better wear resistance owing to their superior indentation characteristics. This results in ropes and fishnets possessing improved abrasion characteristics to mitigate the impact of debris, such as sand particles, during utilization. Enhanced wear resistance is expected to be beneficial in various fibre uses, including upholstery textiles, among others.

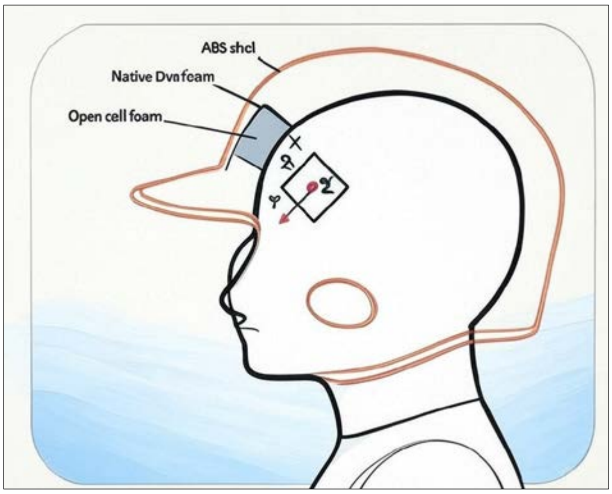
- **Auxetics in Protective Textiles**

Due to its remarkable capacity for energy absorption and shape conformity, auxetic materials are utilized in various protective apparel and gear. In certain high-risk sports like car racing, horse racing, and skiing, safety gear and apparel can shield participants from injuries resulting from impact forces. Protective gear is commonly employed to safeguard sensitive areas, like elbows and knees (Ren *et al*., 2019) [23].

Protective Clothing and Equipment

- **Body armors**

Traditional textile materials used for personal protection tend to be thicker, stiffer, heavier, and less flexible. Therefore, it becomes challenging to transport them to various tropics. Armours constructed from auxetic fabrics can provide comparable protection while being significantly thinner and lighter. Auxetic materials are recognized for their superior ability to absorb shock and vibrations. Auxetic materials exhibit an additional unique characteristic in their response when flexed, taking on a dome-like shape. This unusual characteristic of auxetic materials is beneficial for creating improved body armor, as auxetic body armor can provide equivalent protection while being thinner, lighter, and fitting more closely to the synclastic double curvatures of the human body.

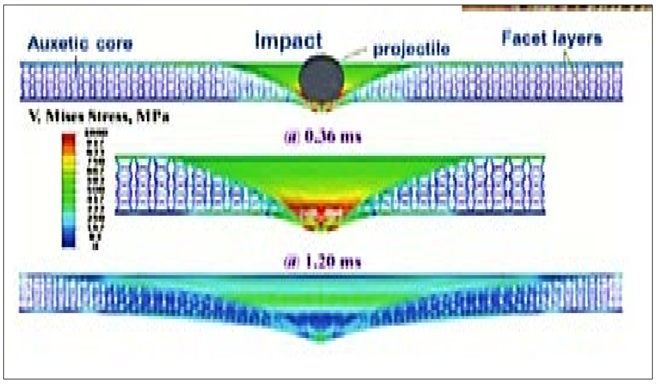


- **Bullet-Proof Helmets and Vests**

Another encouraging application domain for auxetic polymers is enhancing the durability of bulletproof helmets or vests against impacts and shrapnel. When an auxetic helmet experiences an impact from one side, material shifts in from other sides to balance out the impact. Consequently, head injuries could be avoided or potentially less serious. The Defence Clothing and Textile Agency (DCTA) located in Colchester, tasked with researching advanced military clothing, has been investigating the application of auxetic fabrics for defense purposes.

- **Blast Mitigation**

According to Sayed and Samarth, 2019 [27] the existing blast curtain design promotes the utilization of translucent aramid nets that exceed the dimensions of the window in both length and width. The surplus length of the curtain is stored in a box at the bottom of the window. The blast's force frequently tears the net fabric. This is due to the need for the net filaments to be thin to prevent the curtain from obstructing light. Thus, an auxetic fabric that permits light passage while also being able to withstand the immense forces of an explosion and serving as a shield against airborne debris.



AFT'S Xtegra™

AFT's Xtegra™ fabric signifies a groundbreaking advancement in blast-resistant material technology. It is the sole product available that can halt glass and metal shrapnel along with other airborne debris from an explosion due to the auxetic characteristics that allow Xtegra to respond instantly to external forces (Hu and Zulifqar, 2016) [13].

Auxetics in Automotive and Construction

- **Seat Belts**

Auxetic materials provide answers to numerous daily challenges. For instance, think about the way a passenger seat belt reacts during a car crash. During a collision, the occupant is typically propelled forward, and when the deceleration is exceptionally severe, the forces at play can be tremendous. In trying to limit this movement, the seat belt stretches and, similar to an elastic band under tension, grows thinner. In a healthy adult, this can lead to considerable abrasion injuries. For an elderly person, a pregnant individual, or a very young child, these injuries can be considerably more severe. An auxetic seat belt would, however, widen, which would distribute the forces over a significantly larger area, possibly minimizing the severity of any injuries sustained.

- **Smart Sensors - Construction**

Smart sensors can serve as in-situ monitoring tools in numerous masonry and composite structures to detect damage from settlement, earthquakes, terrorist acts, etc. When traditional optical fibre sensors are employed, they typically lack the necessary sensitivity to detect movements in relatively brittle substances like concrete. The innovative sensors created at Auxetic deliver significantly improved signal resolution and offer a variety of additional advantages simultaneously.

- **Smart Sensors - Wearable Computation, Smart Clothing and Fabrics, etc.**

Smart sensors can be applied in numerous fabric-oriented scenarios, such as wearable technology and for gathering data. The new sensors created at auxetic offer significantly better signal resolution compared to traditional optical fibres. A primary use for these sensors is tracking body movements - this could apply to anything from athletes to animals, like racehorses. They can be designed as specialized devices akin to knee or wrist supports, or as standard apparel. An illustration would be the fully-equipped gloves that Auxetic is presently working on. These can be utilized to manage anything from video games to scientific or medical applications. In fact, they might also serve to control machinery through the Internet. They could also be utilized to develop textiles capable of measuring loads like the weight and location of seat occupants or patients in hospital beds (Ali *et al*., 2018) [2].

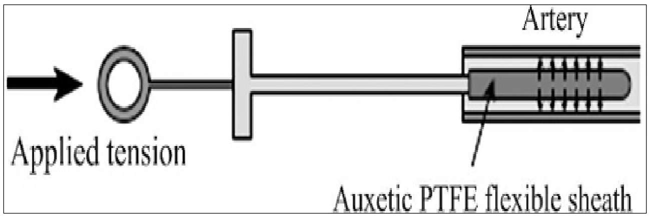
Auxetics in Biomedical Textiles

- **Dental floss**

Auxetic dental floss provides multiple advantages, such as expanding to accommodate the varied spaces between human teeth and the capability to administer chemotherapeutics, fluorides, or flavors straight to the gum line. The auxetic floss's porous characteristics would aid in the removal of debris, enhancing the efficiency of the flossing process.

- **Blood Vessel Dilator**

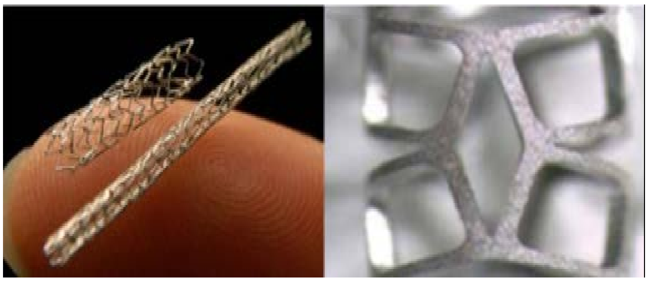
Auxeticmaterials have also been utilized in surgical settings: A dilator, designed to expand the lumen of an artery or comparable vessels, incorporating an auxetic element, has been patented for application in cardiac surgery and associated medical procedures. In this procedure, the coronary artery is widened through the lateral expansion of a flexible auxetic PTFE hollow tube or cover when sujected to tension.



Blood Vessel Dilator

- **Auxetic Stents**

Auxetic stents are intended to widen and maintain the patency of arteries that are obstructed or collapsed. The stent has two crucial needs: to be compact when entering the circulatory system and to expand in length and width upon arrival at its target through a balloon-like mechanism that inflates it. These criteria align seamlessly with the functional range of auxetic materials and structures, making auxetic stents an excellent solution for this medical need (Mazaev *et al*., 2020) [20].



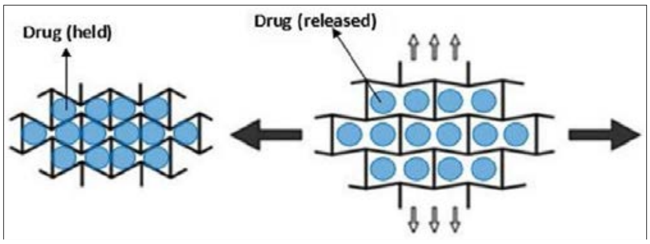
(Left) stents prior to application and (right) a section of an auxetic stent

- **Medical Sutures**

A 'smart-suture' combines braided elements and a wound system, featuring a core that can be saturated with a substance, such as a chemotherapeutic agent. When yarn is pulled, the outer layer enlarges - in doing so, it creates numerous pores - at the same time, it compresses the core, pushing the agent out. This seems to be quite beneficial for in-situ medication administration. For example, if it were infused with vitamin E, it would assist in minimizing scar-tissue development, or if antibiotics were employed, it could be suitable for application in developing nations or on war zones. Another improvement is that the suture's circumference expansion under strain may reduce cheese wire injuries resulting from the suture penetrating the tissue due to patient movement (Liu *et al*., 2020) [19].

- **Smart Medical Bandage**

Auxetic materials can additionally serve for medical stitches and intelligent medical dressings to maintain contact with the healing medication. When the auxetic material is applied to a swollen wound, it stretches under tension to deliver the medication, and once the wound heals and the swelling decreases, the bandage contracts, halting the medication release.

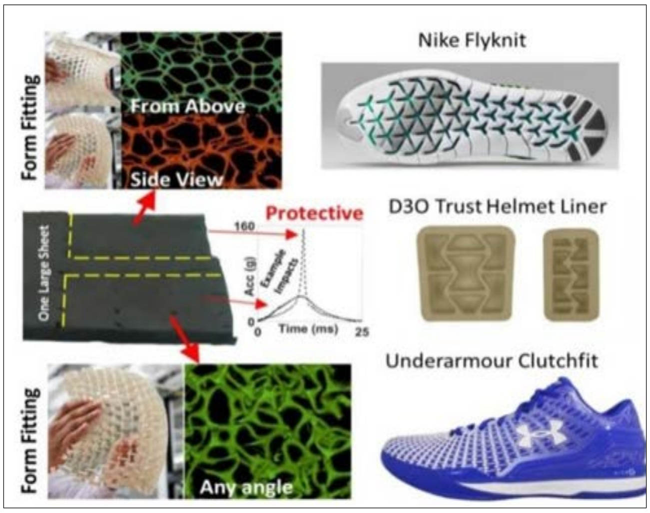


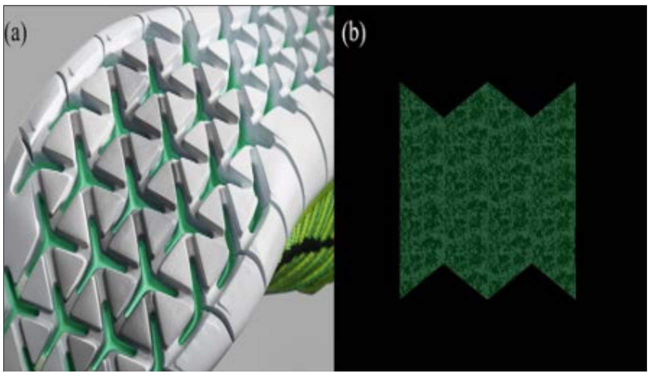
Functional Principle of Smart Bandage

Kim *et al.*, 2021 [16] created auxetic structures through additive manufacturing, soft lithography, machining, compressed foaming, and textile fabrication with several biomaterials, including poly(ethylene glycol diacrylate), polyurethane, poly(lactic-glycolic acid), chitosan, and hydroxyapatite, as well as utilizing a hard material like a silicon wafer. Auxetic structures and their distinctive deformation properties have been studied in various biomedical applications, such as implants, stents, and surgical screws. Despite being in the initial phases, the auxetic structure, capable of generating mechanical properties customized to natural tissue by altering its internal architecture, is anticipated to exhibit enhanced tissue reconstruction capabilities.

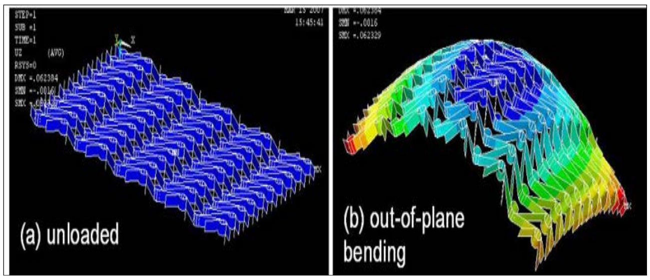
Auxetics in Sports Textile

Auxetics in sports clothing is now a captivating area due to the unusual capability of these structures to "dome," allowing them to conform to the shape of the body (e.g., the bottom of a foot) more effectively than traditional materials. Comfort, resulting from the distinctive shape alteration of auxetics, is a benefit asserted in commercial products. Nike's Flyknit running shoe expands with a runner's foot upon impact, alleviating uncomfortable pressure areas. Underarmour's clutch fit line is said to curve during flexing and adapt to the wearer's foot's anatomical characteristics, a distinctive trait of auxetics. D3O currently sells their 'Trust' helmet padding system, which includes the proven bow-tie shaped auxetic design. Upcoming advancements may feature gradient foam sheets that offer various Poisson ratios, allowing for customization of impact performance and the fit of an individual pad. Intelligent clothing utilizing auxetic and gradient foams may encompass rugby jerseys and protective gear for snow sports (Steffens *et al*., 2016) [31].





Sanami *et al.*, 2014 [24] presented a variety of auxetic materials with potential uses in sports. These involve utilizing auxetic materials in impact protection devices (pads, gloves, helmets, and mats) to take advantage of improved conformability for comfort and support, along with increased energy absorption for lighter and/or thinner components. Finite Element analyses are presented for a novel kind of auxetic honeycomb with potential uses in helmet applications.



'Chiral arrowhead' honeycomb: 5x9 unit cell FE model (a) before and (b) after out-of-plane bending

Simulations of out-of-plane bending revealed distinctive synclastic curvature, affirming that the auxetic effect exists in both in-plane stretching and out-of-plane bending.
Moroney *et al.*, 2018 [22] indicate that recent studies on auxetic materials reveal its promise for personal protective gear in sports clothing, offering improved traits like adaptability, greater energy absorption, and minimized thickness. Conversely, protective materials available on the market have shown to be problematic as they restrict movement, airflow, moisture management, and molded pads tend to saddle. Foam elements are integrated into sports apparel personal protective equipment, with padding placed in areas of the body commonly vulnerable to soft tissue damage from collisions, falls, or impacts.

Auxetic Fabrics for Children and Pregnant Women
Auxetic fabrics can additionally be utilized in the everyday lives of certain specific groups, including children and pregnant women. Children grow rapidly, and their parents often purchase loose-fitting clothing, which can be dangerous for kids as they may trip or get hurt in such garments. Auxetic fabrics featuring folded designs can effortlessly stretch in both lateral and longitudinal directions, making them ideal for children's clothing. They can continue to wear properly fitting clothing for an extended period without concerns that the children may feel uneasy or that they will need to shop again soon.

Auxetic clothing for children, which "grows" alongside their growth
For pregnant women, elastic webbing is typically applied around their waist or abdominal area. The issue is that as their abdomens enlarge, the elastic webbing applies increased pressure on them. Auxetic fabrics can effectively achieve this as they expand both sideways and lengthwise, naturally creating a circular arch that conforms to the shape of the abdomen without applying excessive pressure. Similarly, auxetic materials can be utilized in women's bras and functional sportswear due to their excellent shape-conforming properties, and as safety belts, they may diminish the risk of injuries resulting from concentrated impact forces (Anonymous, 2020) [3, 4, 5].

Size fitting ability of auxetic clothing

Other Applications

- **Danit Peleg 3D Prints Entire Graduate Fashion Collection at home**

For fashion graduate collection at Shenkar, Danit Peleg aimed to create something truly unique. She bypassed the sewing machines and textiles, heading directly to the 3D printers. Utilizing 3D rendering software known as Blender, files were created that Danit began exploring with various materials and printers, aided by 3D printing specialists Tech Factory Plus and XLN; she worked with different printers using polylactic acid plastic (PLA). The material was not to her taste as it was brittle and lacked flexibility. Following nine months of experiments and developments, she discovered fila flex, a robust and highly flexible plastic, with which she crafted intricate textiles, Danit Peleg hopes the fashion industry embraces 3D printing for its customization and ability to produce clothing anywhere, and looks onward to a time when clothing can basically be printed at home (Mizzi *et al.*, 2015) [21].

A skirt by Danit Peleg that uses the stretchiness and bounciness of auxetic materials

- **A Movable, 4D Printed Dress Made with Kinematics**

The Museum of Modern Art (MoMA) in New York has obtained a "4D-printed" dress that shifts its form on its own. Nervous System (design studio) has developed the first 3D printed dress that is movable, designed with 4D printing software, and ready to wear directly from the printer through Kinematics, their 4D printing technology. The dress was created by the 3D printing firm Shapeways in New York as one continuous folded piece and then opened up into its final form. This enables the clothing to be produced more effectively on the compact machines. The allure of this dress, apart from the detailed design, is that it’s tailored to fit perfectly and can truly be worn. The dress is fluid and moves with the body due to the hinge joints between each module.

Flexible, expandable 3D printed dress adapts to body's movement

- **Flexible, expandable 3D printed dress adapts to body's movement**

Designer Maria Alejandra Mora-Sanchez from Houston is leading the charge in 3D printed textiles by debuting a new fashion piece in collaboration with Cosine Additive. Her adjustable 3D printed dress loom is already causing a stir in the textile and additive manufacturing sectors, recently earning Mora-Sanchez a Red Dot Design Award, Design Concept 2017.

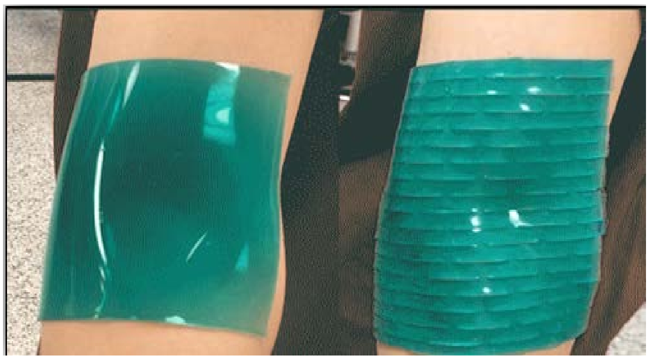
- **The KALIMERO- a portable bike helmet concept**

Clara Clara Schweers, 22 years old, is pursuing Industrial Design at the School of Design at Hochschule Pforzheim. Hailing from Cologne, Germany, the Kalimero was her initiative at Pforzheim. Kalimero is distinguished by its geometric design, allowing for flawless folding, crafted from PVC and polypropylene. This folding method produced a flexible and highly durable surface. Due to the compression of the materials, injuries during an accident can be prevented. The helmet sits on the head perfectly, making contact only in certain areas. This is the reason the haircut includes ventilation and remains unaffected upon reaching the destination. The line of sight is focused on the head due to its alignment. Currently, the helmet is secured using a basic elastic band, allowing the user to fold and unfold it with greater ease (Mazaev *et al*., 2020) [20].

Kalimero Helmet

- **Kirigami Inspires Better Bandages**

Ruike Zhao, a postdoctoral researcher in the Department of Mechanical Engineering at MIT, states that adhesives with kirigami patterns could facilitate a wide range of products, including common medical bandages and flexible electronics. The researchers affixed the "kirigami film" to a volunteer's knee and discovered that whenever she flexed her knee, the slits in the film opened at the center, where bending was most noticeable, while the slits on the edges stayed closed, enabling the film to stay adhered to the skin. The kirigami incisions provide the film with added elasticity and improved adhesion: The cuts that open release tension that would otherwise cause the entire film to peel away from the skin Small, “kirigami” slits in polymer film enable the material to stick to the skin, even after 100 knee bends, associated to the same film without slits, which debonds after just one bending cycle (Valente *et al.,* 2016) [33].

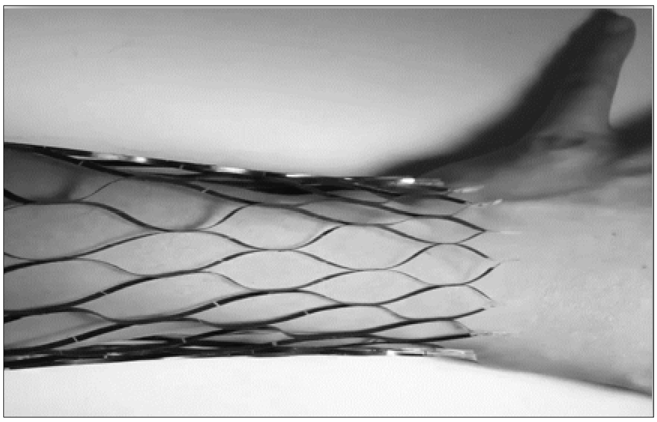


- **Islamic Art Inspires Stretchy, Switchable Materials**

Dr. Rafsanjani from McGill University has developed a novel array of "metamaterials" inspired by the complex, recurring designs prevalent in Islamic art. Metamaterials are designed to possess characteristics that are not found in nature, like expanding in width when pulled instead of merely becoming longer and thinner. These rubber sheets with holes created by a Canadian group achieve this - and then maintain their expanded form until they are compressed once more. These designs may aid in creating expandable stents or parts for spacecraft components. The investigators drew inspiration from patterns, one triangular and one square, found on two Iranian tomb towers (Zhou *et al.,* 2016) [35].

- **Heat-Active Auxetic Materials**

Researchers at MIT’s Self-Assembly Lab have recently created a versatile material that responds to variations in temperature. Referred to as Heat-Active Auxetics, the substance operates similarly to the pores on human skin, contracting and relaxing in response to different temperature exposures. In contrast to conventional auxetic materials, Heat-Active Auxetic Materials exhibit self-sufficient functionality, sensitivity to environmental changes, straightforward customization, and enhanced opportunities for designing and manufacturing material characteristics. Auxetic materials represent a vision for the future of tailored foams, impact protection, packaging solutions, textiles, and numerous other uses that depend on material expansion and contraction.



- **Foldable Screens-100%Merino wool felt**

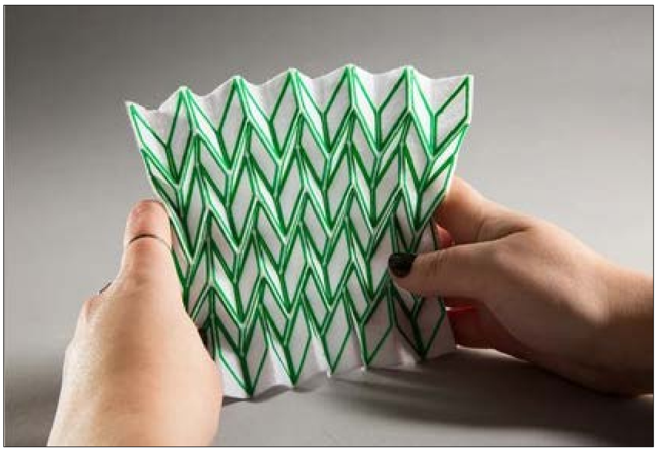
Origanid, France created collapsible displays. Hand pleat, showcasing pleaters’ craftsmanship previously confined to Haute Couture, to convert a sheet into tranquil environments, room dividers, lampshades, bath toys, and wall installations designed to inspire creativity. Sustainable: Covering materials to folds, with packaging, the Furoshiki technique and daily routines, Origanid reduces its ecological footprint and aims for climate neutrality while contributing to local initiatives (Shajoo *et al*., 2021) [28].

- **Oluwaseyi Sosanya invents 3D-weaving machine**

Oluwaseyi Sosanya, a graduate of the Royal College of Art (RCA), has developed a loom for 3D weaving, utilizing it to produce a shoe sole showcased at the college's annual degree exhibition (+ movie). Sosanya has a patent pending for this technology that channels yarn through two tubes and wraps it around a framework of vertical poles. The machine utilizes a layering approach akin to 3D printing, incorporating an additional step to secure the structures without a binder, and interlaces connected layers of straight warp threads and intertwining weft designs at varying heights, creating the third dimension. Sosanya has created a shoe sole using a single continuous thread, showcasing the machine's capabilities while collaborating with designers Lixian (Lisa) Teng and Tomiwa Adeosun. The sole is woven from natural fibres including cotton, wool and paper, and then dipped in silicone to maintain the structural properties (Kwietniewski and Miedzińska, 2019) [17].

- **Conductive Origami Explores 3d Printing onto Textiles to Turn on Light**

Inspired from the techniques of origami folding, Yael Akirav has created 'conductive origami' that investigates an innovative method for activating light fixtures through 3D printing of conductive filament directly onto fabric. The firm printing on the fabric facilitates the production of intricate features and a variety of distinct patterns. When the printed medium carries an electric current, the overlapping folds derived from origami create a novel possibility—illuminating the area by compressing and extending the structure.



Challenges and perspectives of auxetic textiles

The advancement of auxetic materials has progressed swiftly in recent years. Numerous auxetic materials have been found, created, or examined, including fibres, yarns, fabrics, foams, composites, metals, ceramics, and more. Despite the considerable advancements so far, textile specialists have only begun to explore this fascinating and diverse field. The effective creation and advancement of molecular and multifunctional auxetics present significant prospects for the future. So far, only a small number of auxetic fabrics have been created, and they have not been particularly appropriate for clothing applications yet. The creation and production of auxetic textiles using non-auxetic fibres continues to pose a significant challenge for textile experts. Additional systematic research on auxetic fabrics needs to be conducted to maximize the potential of this innovative material derived from textile technology.

The key aspect that requires enhancement is ensuring auxetic fabrics maintain their auxetic properties throughout multiple uses. Greater effort needs to be invested in creating auxetic textiles that offer improved comfort. Further development is required for three-dimensional auxetic fabrics intended to substitute foam pads in protective clothing and smart textiles integrated with auxetic properties. For instance, antibacterial fabrics exhibiting auxetic behavior can expand pores to release medication when worn and contract the pores upon removal by utilizing the variable permeability characteristics of auxetic materials.

Despite numerous suggested uses, actual implementations of auxetic materials remain constrained in the initial phase. Future efforts should focus more on developing new auxetic materials with practical applications. The integration of the auxetic effect with additional features, like shape memory and electromagnetic effect, to create multi-functional auxetic materials should be considered to enhance material properties and applications. Thanks to the work of researchers, it is anticipated that a greater variety of auxetic textile materials will be effectively created for numerous applications in the future (Moroney *et al*., 2018) [22].

Limitations of auxetic textiles

- Auxetic materials require space for their unique micro-structural characteristics to enable the "hinges" to bend, or the "nodules" to expand. The materials frequently require significant porosity.

- These materials are significantly less rigid than the solids they originate from, leading to restrictions on their structural uses with a negative Poisson's ratio.
- Typically, they lack the stiffness or density required for load-bearing uses.

Conclusion

Auxetic materials are metamaterials with a unique structure that includes hinge-like elements, which alter their shape when subjected to force. These materials exhibit a negative Poisson's ratio, causing them to increase in thickness when stretched and decrease in thickness when compressed along their length. Auxetic materials may be either natural or man-made. For example, certain rocks and minerals exhibit auxetic characteristics. Synthetic auxetic materials can possess multiple geometrical structures such as re-entrant, rotating, chiral, foldable, nodule, and fibril, among others. These structures can be produced through various techniques, including laser cutting, 3D printing, folding/spinning, and combination assembly methods. Auxetic materials come in numerous forms, such as polymers, fibres, yarns, fabrics, and composites, suitable for a wide range of intriguing applications. Auxetic materials possess numerous remarkable qualities such as resistance to indentation, synclastic curvature, enhanced fracture toughness, crack resistance, shear stiffness, adjustable permeability, and high energy and acoustic absorption, among others. Because of these outstanding attributes, they find use in a diverse array of applications including furniture, architecture, civil engineering, aerospace, sensors and actuators, protective clothing and equipment, biomedical fields, industrial uses, automotive industries, and sports textiles. Despite the many possible uses suggested, the actual implementation of auxetic materials remains largely in the early stages. Future efforts should prioritize the advancement of new auxetic materials with practical applications.

References

1. Alderson KL, Webber RS, Mohammed UF, Murphy E, Evans KE. An experimental study of ultrasonic attenuation in microporous polyethylene. Appl Acoust. 2010;50(1):23-33.
2. Ali M, Zeeshan M, Ahmed S, Qadir B, Nawab Y, Anjum AS, *et al*. Development and comfort characterization of 2D-woven auxetic fabric for wearable and medical textile applications. Cloth Text Res J. 2018;36(3):199-214.
3. Anonymous. Auxetic Materials Market 2017-2025: Global Industry Size, Share, Growth, Forecasts. https://www.mynewsdesk.com/us/knowledge-hub/pressreleases/auxetic-materials-market-2017-2025-global-industry-size-share-growth-forecasts-2271520
4. Anonymous. Explores 3D Printing onto Textiles To Turn on Light. https://www.designboom.com/design/conductive-origami-yael-ykirav-explores-3d-printing-onto-textiles-08-01-2019/
5. Anonymous. Foldable Screens - 100% Merino wool felt. https://mom.maisonobjet.com/en/product/29564/foldable-screens-100-merino-wool-felt
6. Darijo. Heat-Active Auxetic Materials. http://www.snupdesign.com/heat-active-auxetic-materials-developed-at-mits-self-assembly-lab-4380/
7. Darja R, Tatjana R, Alenka PČ. Auxetic textiles. Acta Chim Slov. 2014;60(4):715-723.
8. Dudek KK, Gatt R, Mizzi L, Dudek MR, Attard D, Grima JN. Global rotation of mechanical metamaterials induced by their internal deformation. AIP Adv. 2017;7(9):095121.
9. Duncan O, Shepherd T, Moroney C, Foster L, Venkatraman PD, Winwood K, *et al*. Review of auxetic materials for sports applications: Expanding options in comfort and protection. Appl Sci. 2018;8(6):941-950.
10. Foster L, Peketi P, Allen T, Senior T, Duncan O, Alderson A. Application of auxetic foam in sports helmets. Appl Sci. 2018;8(3):354-360.
11. Greaves GN, Greer AL, Lakes RS, Rouxel T. Poisson's ratio and modern materials. Nat Mater. 2011;10(11):823-837.
12. Grima JN, Manicaro E, Attard D. Auxetic behaviour from connected different-sized squares and rectangles. Proc R Soc A Math Phys Eng Sci. 2011;467(2126):439-458.
13. Hu H, Zulifqar A. Auxetic textile materials - a review. J Text Eng Fash Technol. 2016;1(1):1-20.
14. Jiang JW, Kim SY, Park HS. Auxetic nanomaterials: Recent progress and future development. Appl Phys Rev. 2016;3(4):44-51.
15. Julia. Flexible, expandable 3D printed dress adapts to body's movement. https://www.3ders.org/articles/20170806-this-flexible-expandable-3d-printed-dress-adapts-to-your-bodys-movement.html
16. Kim Y, Son K, Lee J. Auxetic structures for tissue engineering scaffolds and biomedical devices. Materials. 2021;14(22):68-75.
17. Kwietniewski M, Miedzińska D. Review of elastomeric materials for application to composites reinforced by auxetics fabrics. Procedia Struct Integr. 2019;17:154-161.
18. Lee W, Lee S, Koh C, Heo J. U.S. Patent No. 7,858,055. Washington, DC: U.S. Patent and Trademark Office; 2015.
19. Liu S, Pan X, Zheng D, Liu G, Du Z. The manufacture and characterization of auxetic, self-curling, and self-folding woven fabrics by helical auxetic yarns. J Ind Text. 2020;50(1):3-12.
20. Mazaev AV, Ajeneza O, Shitikova MV. Auxetics materials: classification, mechanical properties and applications. IOP Conf Ser Mater Sci Eng. 2020;747(1):12-18.
21. Mizzi L, Azzopardi KM, Attard D, Grima JN, Gatt R. Auxetic metamaterials exhibiting giant negative Poisson's ratios. Phys Status Solidi RRL. 2015;9(7):425-430.
22. Moroney C, Alderson A, Allen T, Sanami M, Venkatraman P. The application of auxetic material for protective sports apparel. MDPI Proc. 2018;2(6):251-232.
23. Ren X, Zhang X, Xie Y. Research progress in auxetic materials and structures. Chin J Theor Appl Mech. 2019;51(3):656-660.

24. Sanami M, Ravirala N, Alderson K, Alderson A. Auxetic materials for sports applications. Procedia Eng. 2014;72:453-458.
25. Santulli C, Langella C. Study and development of concepts of auxetic structures in bio-inspired design. Int J Sustain Des. 2016;3(1):20-37.
26. Saxena KK, Das R, Calius EP. Three decades of auxetics research − materials with negative Poisson's ratio: a review. Adv Eng Mater. 2016;18(11):1847-1870.
27. Sayed U, Samarth A. Auxetic polymers in textiles - Review. Int J Adv Sci Eng. 2019;5(3):1056-1063.
28. Shajoo S, Schmelzeisen D, Pastore C. Auxetic structures from 3D printed hybrid textiles. Kanbar Coll Fac Pap. 2021;2(1):91-102.
29. Shan S, Kang SH, Zhao Z, Fang L, Bertoldi K. Design of planar isotropic negative Poisson's ratio structures. Extreme Mech Lett. 2015;4:96-102.
30. Srivastava S, Rao AK, Zain M, Kumar R. Utilization of waste rubber fibre considering modification in strength reduction factor and its effect on the behavior of concrete. Mater Today Proc. 2020;21:1489-1495.
31. Steffens F, Rana S, Fangueiro R. Development of novel auxetic textile structures using high performance fibres. Mater Des. 2016;106:81-89.
32. Umut AKSU, Tatlier MS. An investigation on auxetic feature and its applications. Int Adv Res Eng J. 2018;2(2):167-176.
33. Valente J, Plum E, Youngs IJ, Zheludev NI. Nano- and micro-auxetic plasmonic materials. Adv Mater. 2016;28(26):5176-5180.
34. Webb J. Islamic art inspires stretchy, switchable materials. https://www.bbc.com/news/scienceenvironment-35818924
35. Zhou L, Jiang L, Hu H. Auxetic composites made of 3D textile structure and polyurethane foam. Phys Status Solidi B. 2016;253(7):1331-1341.