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# Auxetic Yarn: Fundamentals, Influencing Parameters, Application Areas and Challenges

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## Review

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## ABSTRACT

*The mechanical behaviour of auxetic materials and structures is the most distinctive characteristic, which differs from that of conventional engineering materials due to the negative Poisson's ratio. Auxetic materials have the fascinating feature of widening when stretched and contracting when compressed. In recent times, the research of auxetic materials based on textile structures has received a lot of interest. Auxetic effect development at the yarn phase is a new and exciting field of study. Many researchers already developed different types of auxetic yarns, such as the helical auxetic yarn, the plied auxetic yarn, the semi-auxetic yarn etc. The helical auxetic yarn (HAY) is the most commonly mentioned auxetic yarn. It is made up of a rigid wrap and an elastic core yarn. However, it is interesting that auxetic yarns can be produced from conventional non-auxetic fibres through the conventional spinning system as well. The helical auxetic yarn is a new type of yarn with a wide variety of possible applications. Moreover, pore-opening characteristics of auxetic yarns make it a potential candidate in the fields of technical textiles, such as medical textiles, filter application, protective textiles etc. Fabrication of auxetic textiles by utilizing auxetic yarns through simple weaving and knitting technology opens the door to new applications. The aim of this paper is to address the fundamentals of auxetic yarns, such as structure, shortcomings, production techniques, as well as the influencing process parameters. From various research works, it is evident that the wrap helical angle, the core/wrap diameter ratio, and the initial moduli of wrap component are the most vital processing parameters during the production of auxetic yarns. Finally, some potential application areas and challenges of auxetic yarns are also addressed briefly in this paper.*

## KEYWORDS

*Negative Poisson's ratio (NPR), Auxetic textiles, Helical auxetic yarn, Auxetic plied yarn, Wrap angle*

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## INTRODUCTION

When a material is stretched, it not only gets longer in the stretch direction, but it also gets thinner in the cross-section. The behaviour of the material under deformation in this case is dictated by Poisson's ratio, which is one of the fundamental mechanical properties of materials [1]. Poisson's ratio is defined as the ratio of lateral contractile strain to longitudinal tensile strain [2]. Positive value of Poisson's ratio is found in all common materials, which means they contract transversely under uniaxial extension and extend laterally when compressed in one direction [1]. It varies from 0.0 to 0.5 for most materials [3]. In contrast to

that, auxetic materials have a negative Poisson's ratio (NPR), which implies that when extended longitudinally, they expand laterally, and when compressed longitudinally, they contract laterally (Figure 1) [4]. For instance, cat skin has a negative Poisson's ratio when it comes to natural materials [5].

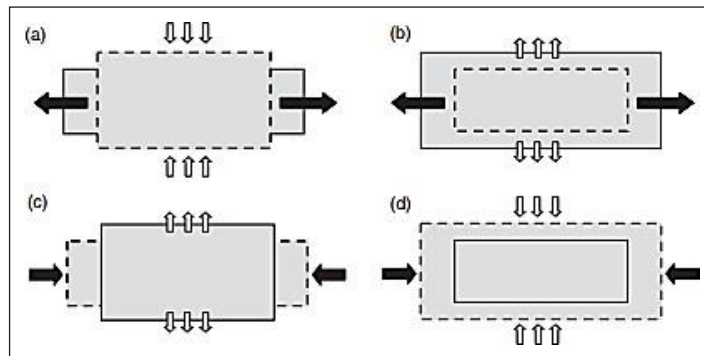


Figure 1. Stretch/compression behaviour: (a) and (c) conventional materials; (b) and (d) auxetic materials [6]

Professor Ken Evans coined the word 'auxetic' in 1991 [7]. The word 'auxetic' originates from the Greek 'auxetikos', which means "which tends to increase" [5,8]. The unusual behaviour of auxetic materials when deformed is intriguing, as well as the fact that having a negative Poisson's ratio can enhance fundamental bulk properties, such as the shear modulus, indentation resistance, fracture toughness and synclastic curvature [1,9,10]. Auxetic materials have a better shape-fitting potential due to the formation of synclastic curvature (Figure 2) when bending [5]. Indentation resistance of an auxetic material is increased as the material flows (Figure 2) into the vicinity of the impact because of the lateral contraction following the longitudinal compression [1]. A crack in the auxetic materials can close up under load due to the negative Poisson's ratio effect [5]. Furthermore, auxetic materials have a greater ability to absorb energy (such as acoustic, ultrasonic, vibrational, and impact) than conventional materials [1,7]. Due to this wide range of interesting properties, auxetic products can be used for a variety of applications, including medicine, construction, civil engineering, sports clothing, high-performance vehicles, explosives safety, insulation, impact-absorbing foams, fasteners, composites, sandwich panels for aircrafts, nanotechnology applications, filters and so on [11,12]. Auxetic materials can be used for making fasteners. The diameter of the fastener shrinks when it is inserted due to the compressive axial force, making it easier to insert. When a fastener is removed, it extends laterally due to axial extension, making it more difficult to remove [6].

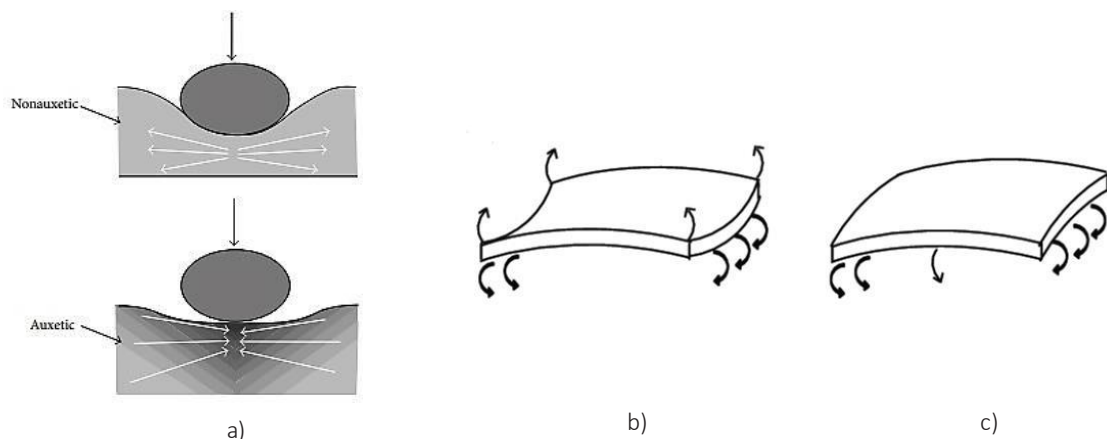


Figure 2. a) Indentation resistance, b) Anticlastic curvature, c) Synclastic curvature [1,6]

However, auxetic materials are a type of material that is relatively new [13]. Several auxetic materials, ranging from macrostructure to microstructure, have been proposed and fabricated in recent years [14]. Auxetic materials can now be obtained from a variety of materials, including polymers, plastics, ceramics, and composites. The auxetic behaviour can be attained at every material size, from microscopic to macroscopic, since the Poisson's ratio is a physical attribute that is independent of material dimensions [3]. There have been several auxetic materials found, manufactured, and synthesized that vary in structure, scale and deformation mechanism [1]. Synthesized auxetic materials are appealing because they enable mechanical properties to be precisely customized for particular applications by adjusting the material structure [9]. The scientific community is becoming increasingly involved in this type of materials. The use of textile technology to fabricate auxetic textile materials including auxetic fibres, yarns and fabrics has received much interest in recent years [3,6]. There are, in principle, two methods for making auxetic textiles. The first method involves knitting or weaving conventional fibres and yarns in a special geometrical arrangement to produce an auxetic impact. The second method is to produce auxetic textiles directly from auxetic fibres and yarns [15]. Steffens et al. mentioned (in introductory section of their paper) that three-dimensional auxetic structures based on warp-knitted spacer structures using polyamide and polyester yarns have lately been developed [11]. The auxetic spacer fabrics have outstanding shape-fitting performance. For example, the auxetic fabric-based maternity dress has fantastic size adaptability and does not wrinkle on the fabric surface. The dress extends in both the waist and the direction perpendicular to it as the belly rises. As a result, the auxetic dress will naturally expand and form a dome shape, which perfectly suits the changing shapes of the abdomen [16]. Auxetic fabric can improve comfort properties (air permeability, thermal resistance, stiffness and wicking) and is more piezoresistive and conductive than non-auxetic fabric, making it a good candidate for medical and wearable clothing [17]. Steffens et al. found that the NPR value of the reinforcing auxetic knitted fabric was transferred from the fabric to the composite. They observed better auxeticity when the composite is produced from auxetic textiles instead of conventional textiles [18,19]. Similarly, NPR characteristics of auxetic yarns can be transferred to the fabric although yarns are incorporated into fabric conventionally [2,4]. Furthermore, composites made of auxetic materials are designed for crash helmets and sports apparels, ropes, filtration, and shock absorbing materials [3]. Auxetic fibre reinforcements can improve the fracture toughness of a composite. This category of materials is often highly fracture resistant; when force is applied, they extend laterally, reducing the development of any possible cracks in the material [20].

The advancement of auxetic yarns has a significant effect on improving the performance of textile materials in general [21]. Auxetic yarns may be used to make fabrics without the need to learn new fabrication techniques [22]. The NPR effect can be achieved by simply weaving or knitting patterns to fabricate auxetic textiles by utilizing auxetic yarns [2]. Auxetic woven fabrics composed of auxetic yarns in both weft and warp directions have been implemented and tested [2,23]. The most widely utilized components for engineering auxetic yarns are high modulus filament combined with an elastic core element [23]. The helical auxetic yarn (HAY) appeared to be the most appropriate structure for the extrapolation, as well as the structure with the highest expectations of maximizing the auxetic result [24]. Moreover, auxetic yarns can be constructed from non-auxetic fibres by using a special configuration [6]. The advantage of using an auxetic yarn over an intrinsic auxetic fibre is the relative ease of tailoring characteristics and the relative simplicity of the manufacturing process [9]. Although there are some reviews of auxetic textile materials [3,6,8], there has not yet been one focusing exclusively on auxetic yarns. In light of that, this paper attempts to summarize the fundamentals of the auxetic yarn along with its progress in terms of manufacturing methods. Furthermore, influencing parameters, potential areas of application and challenges of auxetic yarns are also addressed in this paper.

## FUNDAMENTALS OF AUXETIC YARNS

Staple-spun yarns and long filaments are examples of conventional yarns that exhibit positive Poisson's ratio. Auxetic yarns are primarily made up of various types of yarn components structured in distinct ways [25]. The helical auxetic yarn has recently received a lot of attention. Two components are used to build this novel yarn structure: a thick elastic core and a thin, stiff wrap in the shape of a helically wrapped configuration [23,25,26]. The idea of HAY was first introduced by Hook and Evans [25]. Patrick Hook utilized two conventional yarns in a helical arrangement that resulted in a net increase in the width of the yarn when subjected to tensile strain [9,25]. When the yarn is stretched, the wrap parts and core parts exchange positions. The wrap element straightens; its cross-section will change from elliptical to circular, whereas the former core filament turns to be the wrapper (Figure 3a). As a consequence, the auxetic yarn's outer contour widens. If the yarn is extended any further, the new core (previous wrap) is stretched until it breaks [23]. The outer contour of yarn contracts at first, resulting in a positive Poisson's ratio; then, the outer contour extends, resulting in a negative Poisson's ratio [27]. Following this point, the diameter of the HAY will gradually reduce until the stiff parts within the HAY break (Figure 3b) [28]. The activation strain of the HAY is the strain under which Poisson's ratio first becomes negative [4]. Low strain activation of the yarn is preferred for maximum auxetic effect [9]. The critical tensile strain of HAY is the position when the wrap filament becomes straight (the helical radius of the wrap filament being zero) [27]. The core of a HAY must be more flexible than the wrap. When the core is both compliant and elastomeric, it serves two purposes: it allows for large transverse deformation when strain is applied, and it behaves as a "return spring" when the load is released, returning to its original positioning and rebuilding the original helix in the wrap [13]. The wrap is the more significant portion for regulating the intensity of auxeticity [24]. For the HAY to work properly, the components must have different moduli and diameters [9]. The most popular materials used to make auxetic yarns are high modulus wrap yarn combined with an elastic core yarn [23]. Yarns or filaments with comparatively larger deformation rate, lower tension modulus and larger diameter are selected as core components of the helical auxetic yarn [29]. As a type of hyperelastic yarn, polyurethane was commonly utilized as the core part in auxetic complex yarn [30]. It may be used in the form of monofilament or multifilament [9,23]. Some researchers also used polypropylene, nylon, rubber filament etc. as a core component of auxetic yarns [10,29,31]. On the other hand, polyester, polyamide, Kevlar, carbon, nylon, ultra-high molecular weight polyethylene (UHMWPE), stainless steel monofilament etc. have been used as wrap component of auxetic yarns [9,10,12,23,28,29,31-34].

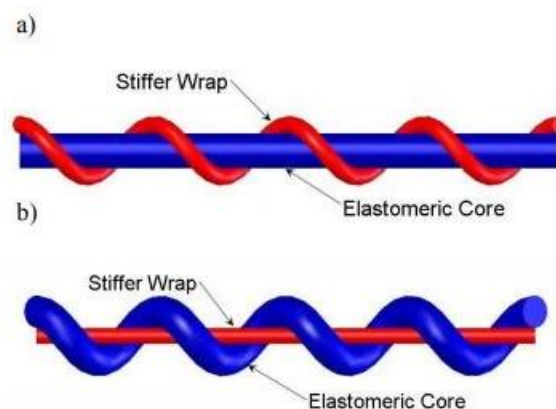


Figure 3a. The helical auxetic yarn: a) initial and b) stretching state [34]

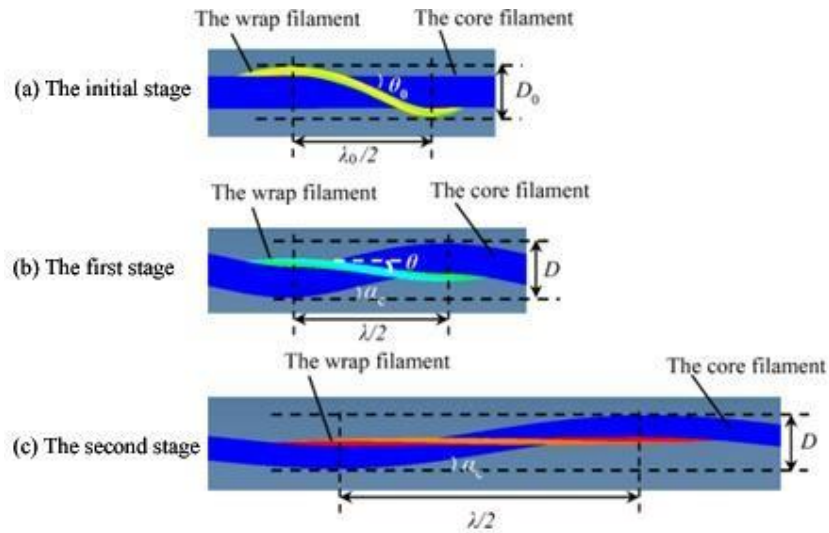


Figure 3b. The helical auxetic yarn: (a) initial, (b) first and (c) second stretching state and [35]

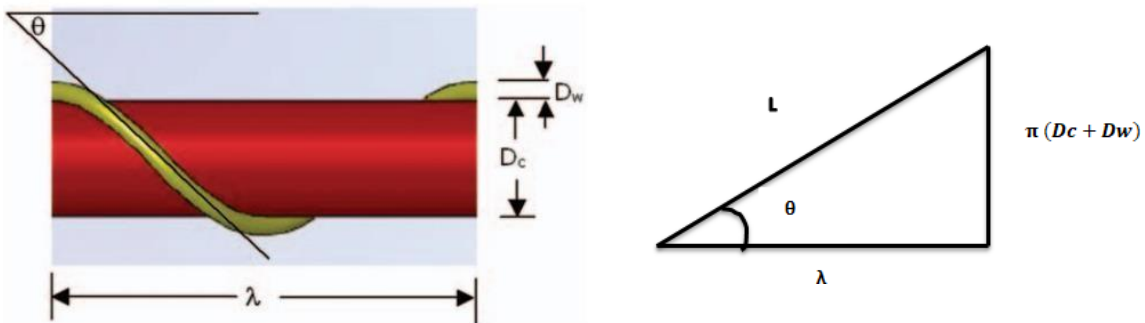


Figure 4a. Geometry of HAY [4,9]

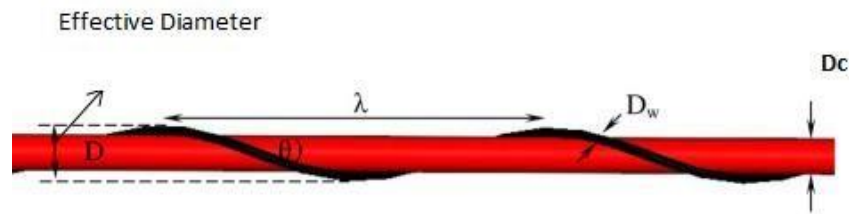


Figure 4b. Effective diameter (D) of HAY [9]

The wrap angle  $\theta$  is defined as the angle formed by the axis of the core and the axis of the wrap at zero strain (Figure 4a). The pitch  $\lambda$  is the longitudinal distance for one complete cycle.  $D_c$  and  $D_w$  are the diameters of the unstrained centre and wrap, respectively. The effective diameter  $D$  of the HAY is defined as the diameter of a cylinder that will adequately encompass the yarn at any given strain (Figure 4b); this is the value that will be used in most realistic applications of the technology. For a material under longitudinal tension, Poisson's ratio is defined as the ratio of lateral contractile strain ( $\epsilon_y$ ) to longitudinal tensile strain ( $\epsilon_x$ ). So, Poisson's ratio is  $\nu = -(\epsilon_y/\epsilon_x)$ . Similarly, the Poisson's ratio of the HAY will be,

$$D = \frac{D_c + 2D_w}{1 + \frac{L}{L_0}} \quad (1)$$

where  $D_o$  denotes the effective diameter of the HAY at zero strain that is equal to  $(D_c + 2D_w)$ ;  $D_c$  and  $D_w$  denote the diameter of the wrap and core respectively;  $L$  is the length at any given strain;  $L_o$  is the length at zero strain. In the unstrained condition, the value of  $D$  is equal to the value of  $D_o$  [4].

$$D = \frac{D_c(D_w + D_o)}{D_w D_o} \quad (2)$$

The cyclic pitch of a yarn can be determined as a function of the ideal wrap angle for any given yarn diameter combination. The pitch is used in the production processes to ensure that the proper yarn geometry is achieved precisely [9].

The auxetic yarn is known as the double helix yarn (DHY) and also the helical auxetic yarn in the literature [22]. However, Miller et al. developed the double helix auxetic yarn with a greater auxetic effect (NPR = -2.1). The stiffer wrapper was made of 220 dtex ultra-high molecular weight polyethylene (diameter= 0.32 mm) and the core was made of polyurethane fibre (diameter= 0.64 mm). The wrap and core components have Young’s moduli of 6 GPa and 53 MPa, and Poisson’s ratios of 0.50 and 0.48 respectively. The wrapping angle was approximately 70°. The DHY resulted in a Poisson’s ratio of -2.1 [34]. Having the same helix angles of wrap and core components is called balanced DHY [36]. Sloan et al. developed a HAY with a polyurethane core (Young’s modulus of 30 MPa) and a polyamide wrap (Young’s modulus of 3.4 GPa). For the yarn with a 13° wrap angle and a core to wrap diameter ratio of 4.2:1, this HAY showed the Poisson’s ratio as low as -2.7 [9].

However, the HAY have certain inherent structural shortcomings. The first weakness is that the rigid wrap can simply slide over the surface of the core yarn, making it challenging to twist yarn in a consistent manner. Second one is that its rigid wrap can easily become loose after expansion, resulting in low yarn structural stability [37]. Moreover, due to the core’s compliance, there’s a chance that an unfavourable feature will emerge inside the HAY. The wrap may indent the surface of the core and insert itself into the core when the HAY is under tension (Figure 5). As a result, the negative Poisson’s ratio and the auxetic behaviour could be decreased [12,13]. Besides, the core-indentation mechanism of the multifilament wrap component differs from that of the monofilament wrap on the HAY yarn [13].

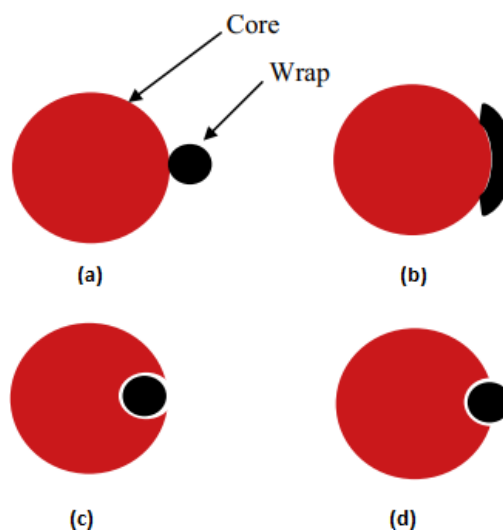


Figure 5. (a) Ideal HAY, (b) wrap spread around core, (c) partial and (d) entire core-indentation [13]

Plied yarns are also used to make auxetic yarns. The auxetic plied yarn's deformation mechanism differs from the DHY, where the auxetic characteristic is induced through the stiff yarn migration in the plied structural system. As the auxetic yarn is extended along its longitudinal direction, the stiff yarns appear to move to the centre and force the soft yarns outward [15]. The auxetic plied yarn will have its own geometrical and mechanical factors at the yarn level that can govern or affect the NPR action and the amount of the open area of the final fabric to some extent. Ge et al. produced a helical auxetic yarn with a 4-ply structure. The new HAY structure was composed of four kinds of yarn with two stiff yarns and two soft yarns. Two stiff yarns were spiralled around the two soft yarns positioned in the centre to form a 4-ply helix structure. When the 4-ply auxetic yarn is extended longitudinally, the stiff yarns move toward the core. As a result, stiff yarns will be positioned in the centre and the soft yarns will move outward (Figure 6). As a consequence, the auxetic yarn will expand in the lateral direction. The next stage is realized from the first contact of the two stiff yarns to the final breakage of the auxetic yarn [37]. Ng et al. produced 6-ply auxetic yarns and reported on their auxetic behaviour as well. However, they compared the NPR among the DHY, the 4-ply and the 6-ply auxetic yarn (Figure 7) and concluded that the 4-ply auxetic yarn has a greater NPR result than the other two auxetic yarns [2]. Compared to the DHY which has a filament helically wrapped around a barely twisted filament and is unstable, the auxetic plied yarn is more robust. The plied structure enables the auxetic yarn to enhance its twist regularity [15].



Figure 6. 4-ply auxetic yarn: (a) at rest; (b) under extension; and (c) cross-section views at different stages of stretching [2]

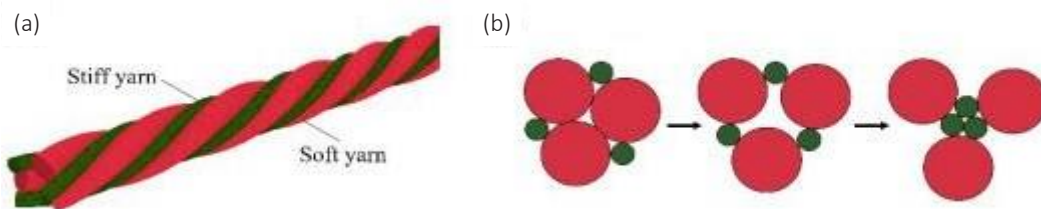


Figure 7. 6-ply auxetic yarn: (a) side view, (b) cross-sectional view at different levels of stretching [2]

Liu et al. introduced a novel interlaced-helical auxetic yarn composed of one compliant yarn and two stiff yarns (Figure 8). The two stiff yarns are symmetrically wrapped around the core and the core is located at the centre of the interlaced helical yarn. As the axial strain increases, the stiff yarns deform from being helically wrapped to being straight whereas the core deforms from being straight to the state of a sinusoidal curve. According to Liu et al., the interlaced-helical complex yarn has advantages over the helical wrap yarn with the same materials and the initial wrap angle in terms of structure stability and auxetic performance. The value of the Poisson's ratio for the yarns was -2.8 [32].



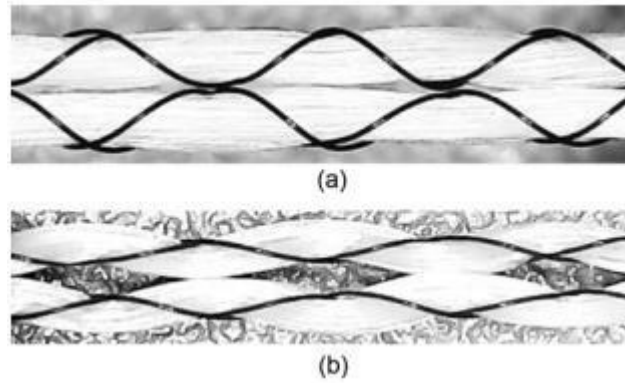


Figure 8. A pair of interlaced helical auxetic yarns; (a) initial state and (b) stretching state [32]

The auxetic yarn can react to both external force and moisture [10]. By incorporating moisture-triggered shrinking filament, Lee et al. produced an auxetic yarn that not only reacts to externally applied force but also to moisture. A moisture-sensitive filament and a low-modulus elastic filament are used to make a moisture-sensitive auxetic yarn. When a load (tensile or shrinking) is added to the thread, the previously wrapped yarn appears straight and the elastic components shift in an opposite direction. Thus, an overall auxetic effect is achieved for the entire group of yarns [32].

Lim explored the idea of a semi-auxetic yarn by sewing an inextensible thin yarn through an extensible thick yarn in a triangular configuration (Figure 9). The thin yarn straightens as the thick yarn turns into a curved yarn with consistent wave length during yarn extending, resulting in lateral extension on the auxetic plane but transverse contraction on the conventional plane. Inextensible thin yarns can come in the form of a trapezoidal waveform, a rectangular wave, a sinusoidal wave, or a triangular wave (Figure 10). The ability of a yarn to show both conventional and auxetic nature in various planes opens up possibilities that neither a conventional yarn nor a fully auxetic yarn could accomplish. Lim mentioned that the use of semi-auxetic yarns provides for excellent positive and negative Poisson's ratios. For instance, a high initial half-angle ( $= 60^\circ$ ) would result in (a) a very high positive Poisson's ratio of 0.906 on the conventional plane if the thick yarn has the Poisson's ratio of 0.5, and (b) a very NPR value of -4.82 on the auxetic plane if the thick yarn has the Poisson's ratio of 0. Thus, a semi-auxetic yarn will exhibit both the conventional and the auxetic effect, while also permitting the degree of Poisson's ratio on both planes to be adjusted. The Poisson's ratio of the semi-auxetic yarn on the conventional plane is primarily governed by the PR of the thick yarn, whereas the PR of the semi-auxetic yarn on the auxetic plane is controlled by the initial half-angle of the thin yarn [38].

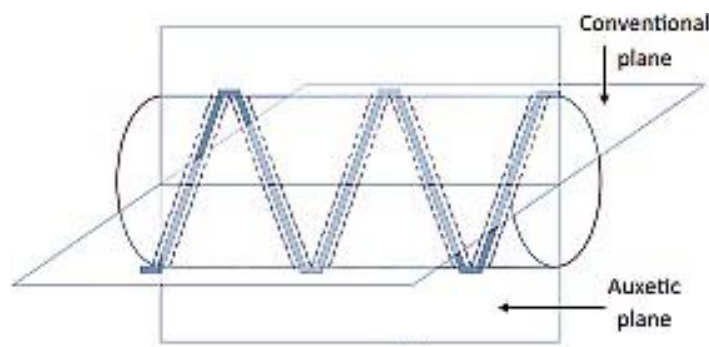


Figure 9. The auxetic and conventional planes of the semi-auxetic yarn [38]

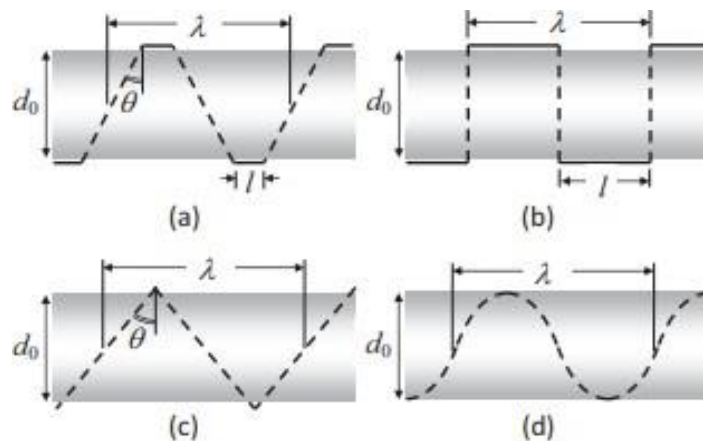


Figure 10. Different types of semi-auxetic yarns: (a) trapezoidal wave, (b) rectangular wave, (c) triangular wave, and (d) sinusoidal wave [38]

Since helical auxetic yarns have a high capacity for augmenting the auxetic impact of fabric, their structure may be considered as the most suitable for conducting research [21]. Most of auxetic woven fabrics has been developed by employing helical auxetic yarns and following a regular interlacement pattern, either as warp or as weft [39].

### AUXETICITY AND PORE OPENING OF ASSEMBLED YARN

The auxetic impact of the HAY is subjected to particular yarn configurations. When the yarns are assembled out of phase, each HAY stretches and pushes the adjacent HAY; this pushing effect results in the overall expansion of the yarn group and the auxetic effect. When the yarns are positioned in phase, indeed, the yarn's expansion only induces a small increment in the transverse direction of the entire yarn group (Figure 11). As a result, it is mentioned that the HAYs can achieve the maximum auxetic result only when they are positioned out of phase [25]. Pores will arise as a consequence of the deformation of the yarn constituents when a complementary pair of auxetic yarns is extended. There are potential applications in filtration, fluid transfer (e.g. drug delivery) etc. by utilizing the feature of the pore opening phenomenon generated in the structure of the assembled auxetic yarn (e.g. fabric).



Figure 11. Out of phase (top) and in phase (bottom) arrangement of HAYs [25]

### PRODUCTION TECHNIQUE FOR HAY

The auxetic yarn was successfully acquired through a ring-spinning method with a wrap filament and a core filament [40]. However, the residual torque of HAYs produced by ring spinning is high, which limits their use. The residual torque could cause the wrap part to slip away from the core in its natural state, resulting

in poor stability and applicability [32]. The residual torque of auxetic yarns produced by the hollow-spindle covering method is lower than that of the ring-spun yarn, and yarn stability is greatly improved (Figure 12a) [28]. Jiang et al. developed a new type of auxetic yarn constructed with circular braiding technology to solve the yarn slippage phenomenon in the typical helical auxetic yarn structure. They produced the auxetic yarn by changing the number, the arrangement of stiff yarn and the diameter of core yarn [41]. Two stiff yarns as wrap components were interlaced helically and wrapped around a compliant core yarn to create a novel complex auxetic yarn by a braider. The feeding of the compliant core yarn is provided through the opening tube in the centre of the braider's fixed foundation, as shown in Figure 12b. The auxetic yarn structure is developed at the collector point when the two stiff yarns bind it helically with the rotation of the bobbins. The wrap angle can be modified by varying the yarn element feeding speed [32].

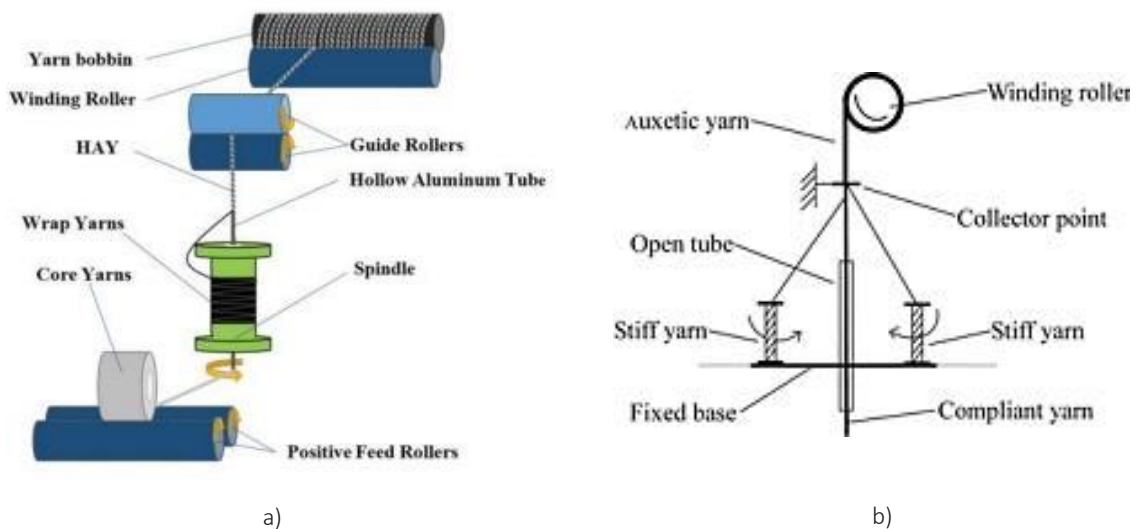


Figure 12. a) Hollow-spindle covering system [28] and b) The braider for producing HAY [32]

Ge et al. produced HAY from two stiff and two soft yarns using a plying technique (Figure 13a). Two soft and two rigid yarns were alternately positioned and fed from a revolving circular disk for plying purpose. By modifying the rpm of the rotating disc and the take-up speed of the auxetic yarn, the twist of the yarn can be derived. The NPR impact of the novel auxetic plied yarn was obvious [37]. Zhang et al. developed a semi-coextrusion method (Figure 13b) for the mass production of helical auxetic yarns with a consistent wrap angle. The core fibres remain fully intact as they run through the revolving die's centre without melting. When the wrap components are hot, extruded at the tip of the revolving die with a pre-formed helical configuration, the two portions (i.e., wrap and core) bind securely once the extruded wrap components are cooled and create a repeatable and regulated wrapping angle at a constant tension. The wrap angle of HAY can be controlled by regulating the semi-coextrusion die's speed of rotation. Because of the benefits of the pre-formed helical wrap component, Zhang et al. claim that semi-coextruded HAYs have a higher maximum negative Poisson's ratio and thus better auxetic efficiency than conventional HAYs [33]. Some researchers produced auxetic yarns by using a lab-scale spinning device (Figure 14a). For example, Ng et al. produced DHY, 4-ply and 6-ply auxetic yarns [2]. Furthermore, Sloan et al. produced helical auxetic yarns using a lab-scale spinner mechanism (Figure 14b).

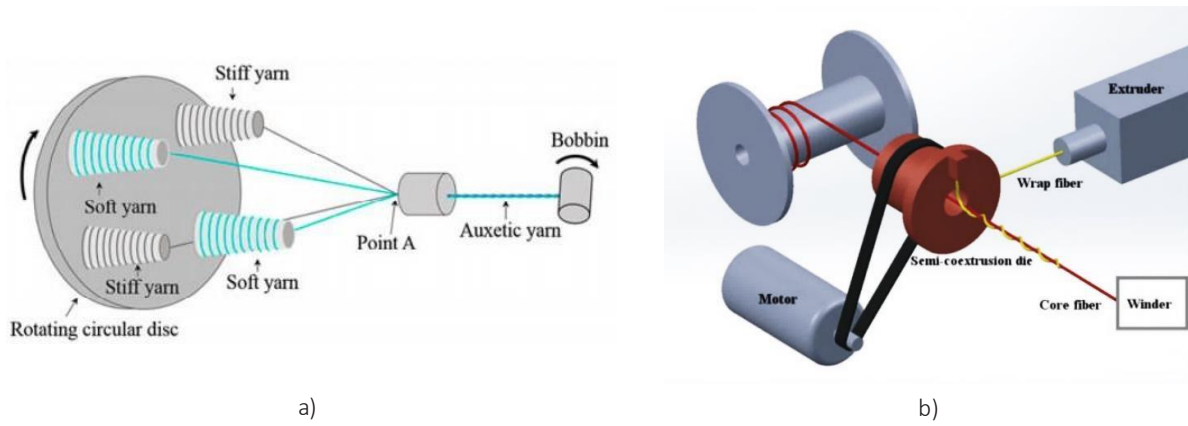


Figure 13. Manufacturing process of a) plied auxetic yarn [35] and b) semi-coextruded auxetic yarn [33]

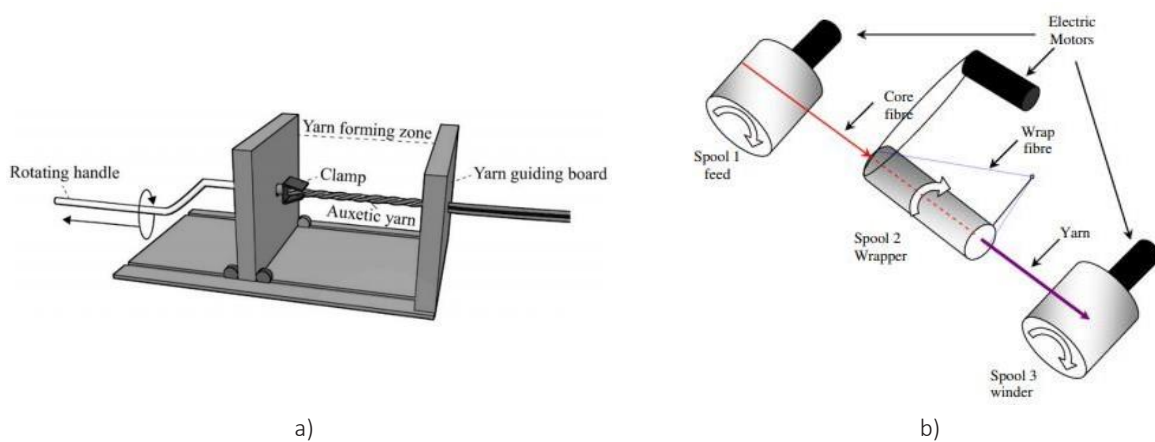


Figure 14. Lab scale spinning devices for HAY: a) Ng. et al. [2] and b) Sloan et al. [9]

Table 1 shows the basic differences between the helical auxetic yarn and the auxetic plied yarn (APY).

Table 1. Comparison between the helical and the plied auxetic yarn

Features	HAY	APY
Construction	The HAY is formed with one low-stiffness thick core filament and one high-stiffness thin wrap filament. These two filaments are helically wrapped around each other.	The APY is formed with more than two components. For instance, to make a 4-ply helix construction, two soft yarns of a relatively large diameter are put in the central position while two rigid yarns spiral around them.
Auxetic mechanism	When the HAY is stretched, the wrap filament will move inward to the core of the yarn and push the core filament outward, thus increasing the width of the yarn.	The APY is generated by the migration of stiff yarns to the centre of the plied structure, forcing the soft yarns outward. As a result, the maximal width of the auxetic yarn is obtained.
Twist regularity	The stiff wrap can easily slip along the surface of the core yarn, resulting in the difficulty to make very regular yarn in twist.	The twist regularity of the APY is higher than that of the HAY.
Stability	Structural stability is poor since the stiff wrap can easily get loose after extension.	Structural stability is robust.
Production method	Ring spinning, hollow spindle spinning etc.	Braiding technology, twisting machine etc.

## INFLUENCING PARAMETERS

Several structural and material variables can have a major impact on auxetic performance, since the auxetic behaviour of textile materials is highly influenced by their structural mobility and rearrangement under mechanical deformation [23]. Many researchers studied the parameters influencing the process of auxetic yarn production [9,13,15,27-29,33,40]. Various structural factors of the core filament and the wrap filament, including diameter ratio, helical angle and tensile modulus of the wrap filament are recognized the most influencing parameters of the auxetic yarn production. These parameters need to be optimized accordingly in order to obtain the maximum auxetic behaviour of the HAY. Adjusting even one of the variables in the structure may generate large NPR values. For example, Bhattacharya et al. fabricated a HAY with a strong negative Poisson's ratio of -13.52 by using the right combination of part moduli and geometric parameters [13].

### Initial Wrap Angle

The initial wrap angle is the most important engineering factor that affects the auxetic behaviour of a yarn [33]. The angle formed by the axis of the core yarn and the axis of the wrap yarn at zero strain is known as the wrap angle of the helical auxetic yarn [4]. However, the intensity of auxetic behaviour is shaped by the initial angle of the wrap part. When engineering, the auxetic behaviour is not obtained when the initial wrap angle is high [9,42]. More wraps per unit area of the core are indicated by a higher wrap angle. So, for the same length of core yarn, a greater number of wraps per unit area means a longer wrap yarn in the HAY [10]. Miller et al. produced the HAYs with a nylon core (Young's modulus of 1.6 GPa and the diameter of 0.7 mm) and a carbon wrap (Young's modulus of 143 GPa and the diameter of 0.2 mm) and they achieved Poisson's ratios of -5.8, -2.3, and -1.1 for 10°, 20°, and 30° wrap angles respectively [31]. Ming et al. studied the effects of 20°, 30° and 45° wrap angles on HAYs and they found the best NPR result for the 20° wrap angle compared to the other two angles [29]. Miller et al. also made a DHY with a wrapper of carbon fibre (diameter = 0.2 mm) and a core of drawn monofilament nylon fibre (diameter = 0.7 mm). DHYs of 10°, 20°, and 30° wrap angles had average Poisson's ratio values of -5.8, -2.3, and -1.1, respectively [31]. Du et al. produced spun helical auxetic yarns with helical angles of 35°, 30° and 25°, respectively, by using a spandex filament (linear density = 124.4 tex) as the core and a nylon filament (linear density 16.7 tex and tensile modulus of 0.93 GPa) as the wrap. They found NPR values of -0.64, -1.04 and -1.88 for helical angles of 35°, 30° and 25°, respectively [40]. Gao et al. found the NPR values of -5.62, -1.50 and -0.42 for the helical wrap angles of 25°, 34° and 39°, respectively [23]. Sloan et al. concluded that the magnitude of the auxetic behaviour is governed by the initial angle of the wrap yarn [9]. Ng et al. also studied the effect of the twist level (i.e., 35, 51, 65 twist/meter) on the deformation behaviour of the 4-ply auxetic yarn structure and they reported that the degree of auxeticity is reduced with an increase in twist level at low strains. They explained that the binding effect of the twist causes the 4-ply auxetic yarn structure to become more compact as the twist amount is increased. As a result, stiff yarn migration is hampered, and auxetic output suffers as a result [15]. In contrast to that, HAY with a higher initial wrap angle consume more energy than HAY with a lower initial wrap angle since it takes more time for their wrap component to straighten and break. So, there is a competition for the best initial wrap angle, seeing as auxeticity necessitates a low value, while energy absorption necessitates a high value. According to Zhang et al., the best combination of energy absorption and auxetic efficiency of HAY has been found at a 27° initial wrap angle [43]. It is worth mentioning that fabrics production with a low helical angle is not suitable due to a poor structural stability [23].

## Tensile Modulus of Stiff Yarn

The big tensile modulus difference between the two components results in position exchange and deformation behaviour [35]. The outer contour improvement during stress is influenced by the wrap filament's tensile modulus. Yarns with a higher modulus wrap component have a greater negative Poisson's ratio effect in general [27]. Bhattacharya et al. investigated the influence of the interaction between the core and the wrap yarn on the auxetic performance of the helical auxetic yarn. It revealed that the core/wrap moduli ratio needs to be high enough to generate an auxetic result and low enough to remove the core-indentation phenomenon in order to create yarn with the highest negative Poisson's ratio [13]. Chen et al. concluded that a large NPR of the HAY can be acquired with a wider core yarn diameter and a higher tensile modulus. When the stainless steel monofilament was used as the wrap component, they found the maximum NPR of -2.55, compared to polyester's -1.89 [28]. Ming et al. obtained NPR values of -4.3, -3.1 and -1.7 for the wrap yarn's modulus of 1.72 GPa, 0.93 GPa and 0.34 GPa, respectively [29]. Du et al. also achieved a similar pattern of NPR results in their experimental verification [40]. The NPR of the 4-ply auxetic yarn structure is also influenced by a higher tensile modulus of the stiff yarn. The components with a higher tensile modulus appear to cause inward migration when the 4-ply auxetic yarn is extended. If the tensile modulus difference between soft and stiff yarns widens, more hoop tension is developed in the stiff yarns' helices, resulting in higher migration intensity [15].

## Diameter Ratio of Core to Wrap

The ratio of core to wrap fibre diameters is another geometric parameter that is used to tailor the auxetic effect [9]. With a larger diameter ratio of the core filament to the wrap filament, the auxetic effect becomes more pronounced under stress. It may be demonstrated by the fact that as the diameter of the core filament decreases in comparison to the diameter of the wrap filament, the length of the wrap filament in one helical unit decreases as its helical angle remains constant. As a result, for the same span of the core filament as the wrap filament, there is more compressional interaction and the core component experiences more cross-sectional contraction as a result of the wrap filament's stronger compressional force per unit length. So, under the same longitudinal load, the wrap yarn displaces the core yarn and extrudes it even more intensely with a larger diameter ratio [27]. Ming et al. concluded that the result of the Poisson's ratio becomes more apparent as the diameter ratio of core to wrap changes [29]. Du et al. varied linear densities of the core filament as 93.3, 124.4 and 186.7 tex during the production of auxetic yarns while keeping the linear density of wrap filament as a constant (16.7 tex). The obtained NPR values were -1.32, -1.52 and -2.01, corresponding to linear density ratios of 93.3:16.7, 124.4:16.7 and 186.7:16.7, respectively [40]. Some researchers theorised that downsizing the diameter of the carbon based wrap yarn from micron to nanoscale will generate a larger negative Poisson's ratio in the DHY [36]. However, the wrap should preferably be infinitesimal in diameter while ensuring a relatively high stiffness to optimize the auxetic behaviour, but in practice, there will be practical concerns and cost issues in using very thin high modulus wraps [42].

## FIELDS OF APPLICATION

High cost and a complicated manufacturing technique of auxetic fibres for producing auxetic textiles can be minimized by using auxetic yarns made of non-auxetic fibres. Another benefit of having an auxetic yarn over an inherent auxetic fibre is the relative simplicity of tailoring properties [9]. However, the helical auxetic yarn is a novel yarn construction that has a wide variety of application fields [4]. In real-world strain regimes,

the HAY is auxetic and is best suited to woven fabrics, although knitting is also achievable. However, individual HAY can be used for dental floss, sutures, and optical sensors [33]. It is recommended that HAY can be utilized for technical auxetic textiles and combined in a composite which could be used for making body armour and for blast mitigation (catching the debris generated by a bomb explosion) purposes [24]. The multiple layers of the porous structure are ensued by using the pore opening ability of the auxetic yarn in the textile structure. It allows energy from the blast to be proficiently dissipated through different layers and voids created in the structure, thus reducing the explosion impact [3]. Miller et al. developed a multi-layered composite with a large NPR value obtained by using the double helix auxetic yarn [34]. The HAY can be used in braided, flat, and tubular fabrics, and it has potential applications in healthcare [8].

The pore-opening characteristics of HAY also enable its application in filtration, where deliberate scaling of tensile or compressive load application serves as a mechanism to regulate the filtration operation by varying the pore size [3]. Leveraging the ability to cause pores to open in a fabric made with HAYs permits a number of potential application areas with technological benefits, such as drug delivery, transfer/removal of, for instance, a wound exudate, or visual indication by exposing of a substrate to induce colour change [8]. The smart bandage is also one of the examples. Auxetic filaments may be used to produce a bandage that contains a wound-healing agent. The bandage will open up and release the agent as it is applied to the swollen wound (Figure 15). When the wound heals and the swelling goes down, the bandage will close and the agent will be released [6]. When a non-auxetic bandage is employed for such purposes, higher pressure occurs on the wound, as well as a reduction in porosity, obstructing wound healing [17]. Antibacterial, antiviral, antifungal, antiyeast, and antiamebic agents are among the various compounds that could be retained in the porous material [3]. The fabric can produce a colour effect (Figure 16) under strain when HAYs are employed to produce fabric woven with a special pattern. Because of their unique yarn structures and pore-opening outcome, fabrics constructed by helical auxetic yarns are a smart idea for fashion design and other areas where a correct indication of tension is necessary [4,16].

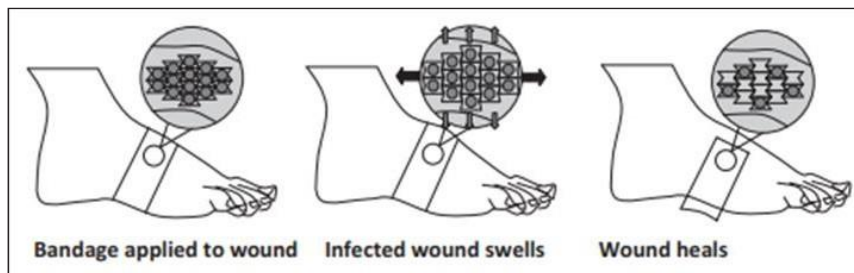


Figure 15. Smart bandage [6]

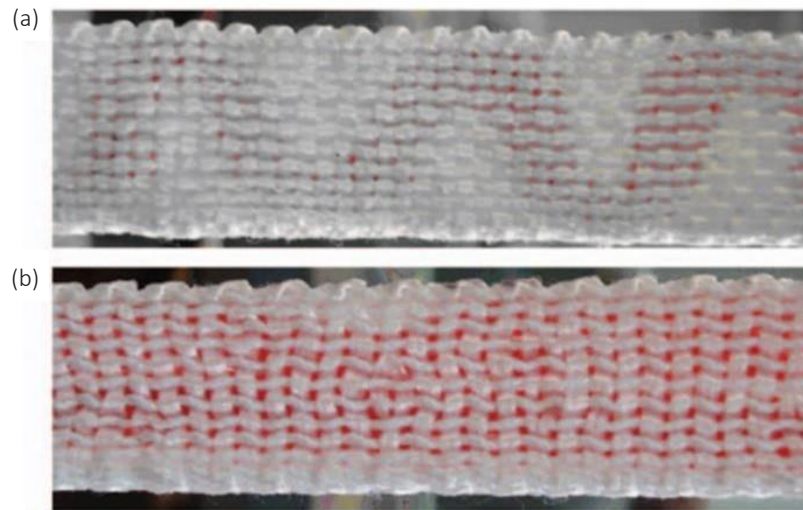


Figure 16. Colour change in the fabric because of pore opening; (a) 0 N tension, (b) 80 N [4]

Chen et al. developed and fabricated a negative Poisson's ratio yarn (NPRY) combined with triboelectric nanogenerators (TENGs) to be utilized as a foundation structure in a variety of versatile textile-based electronic devices, including an energy harvesting cloth, a self-counting yoga elastic band, and a self-powered pre-alarm cable. As a foundation structure material, this unique, low-cost, and highly efficient NPRY has great potential in the production of all types of textile-based TENGs as well as the harvesting of a large amount of random energy from the surroundings [44]. Geo et al. observed that auxetic fabrics possess increased air permeability and higher energy absorption compared to non-auxetic fabrics. Thus, the structure made of the auxetic yarn is suitable for acoustic and impact absorption applications [23]. Furthermore, fabric produced from the auxetic yarn increases the mechanical properties [21]. According to Lim, the semi-auxetic yarn could be used to weave a semi-auxetic fabric. For instance, semi-auxetic woven fabric can be applied in safety belts or other related devices in which dimensional stability in the fabric's width direction is required [38].

## CHALLENGES FOR THE AUXETIC YARN

As auxetic yarns are made of extensible components in their structure, they have a high initial extension which is a big obstacle while being processed on high-speed machines. Gao et al. reported that auxetic yarn with high initial extension was not suitable for fabric production [23]. Mass production of auxetic yarns is also a concern. Furthermore, the auxetic response of the fabric made of the auxetic yarn is not still remarkable. Realizing the auxetic plied yarn's NPR behaviour isn't enough to anticipate its consistency in a fabric. For this reason, some researchers are trying to focus on obtaining auxeticity from the fabric stage [17]. However, the engineering design of auxetic fabric for utilizing the auxeticity of the yarn in its structure necessitates further experimental study. For example, Gao et al. found maximum NPR of -0.052 in the weft direction and -0.025 in the warp direction for woven fabric made of HAYs in both the weft and warp directions, much lower than that of the auxetic yarn (NPR = -5.6) [23]. Wright et al. produced auxetic yarns with the NPR value of -1.5, whereas the auxetic fabrics exhibited the NPR value of -0.1 [4]. Ng et al. also observed a similar pattern of substantial NPR value reduction in fabrics made from auxetic yarns with a high NPR value [2].

However, there are still huge hopes of producing different types of auxetic yarns from different materials along with the process parameter optimization. Producing auxetic yarns on a large scale is one of the challenges to be addressed more and more by researchers in the future. Owing to the short development period,



the creation of auxetic textiles by utilizing the auxetic yarn is still in its research phase. It still has a long way to go, particularly in the context of application areas, which requires considerable planning. The auxetic yarn technology will undoubtedly advance further through product innovation. The helical auxetic yarn, the semi-auxetic yarn and the plied auxetic yarn need to be studied further for their application potentiality in smart textiles, such as wearable electronic textiles, environment protective filters etc. More importantly, the popular spinning system for micro/nanoyarn production needs to be explored in the future with the aim of producing auxetic yarns. Researchers may also address the manufacturing of auxetic yarns from high-performance fibres. It is desired for more sophisticated structures employing auxetic yarn assemblies to be produced for novel applications including apparels. Furthermore, research studies should focus on ameliorating the properties of the auxetic yarn in order to incorporate functional activity in the textile products.

## CONCLUSION

Auxetic yarns are a relatively new class of functional materials. They possess a negative Poisson's ratio, which differs from the conventional yarns or filaments. Incorporation of these auxetic yarns in the fabric structure done by simple weaving and knitting technology leads to the fabric exhibiting auxetic behaviour. However, this paper recapitulates the fundamental understanding of auxetic yarns, including their types, geometry and manufacturing methods. Generally, auxetic yarns are manufactured based on a conventional helical structure. The helical auxetic yarn and the auxetic plied yarn are two prominent types of auxetic yarns. Effects of various process parameters, such as the initial wrap angle, the core to wrap diameter ratio, and the elastic modulus are also discussed herein. Mostly, the degree of the auxetic effect and the resulting properties of the auxetic yarn are highly affected by these parameters. Appropriate combination of component moduli and geometric parameters is necessary in order to facilitate the fabrication of the auxetic yarn with a large negative Poisson's ratio. Pore opening characteristic of auxetic yarn is a very interesting phenomenon, opens the door to many potential applications, such as filtration, composites, health-care, blast mitigation, protective textiles, colour changing fashion apparel and so on. However, there are still huge issues to be addressed associated with auxetic yarns, e.g., transferring auxetic behaviours from yarn to fabric. This yarn technology will advance with further research in the near future as the potential of this yarn structure starts drawing the interest of many researchers.

### *Author Contributions*

All authors contributed to the final manuscript. All authors provided critical feedback and helped to shape the final manuscript.

Conceptualization – Md. Khalilur Rahman Khan conceived and planned the study; Methodology – Abu Bakr Siddique and Hosne Ara Begum developed the framework; Writing original draft preparation – Md. Khalilur Rahman Khan wrote the manuscript. Writing-review and editing – Md. Khalilur Rahman Khan. All authors have read and agreed to the published version of the manuscript.

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### *Conflicts of Interest*

The authors declare no conflict of interest.

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