Chapter

Textiles Functionalization - A Review of Materials, Processes, and Assessment

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Abstract

Conventionally, textiles are known to cover up the human skin, but by scientific administration, clothing can be extended to serve other human skins' functions. Accepting the chemical and dermatological complexity of human skin, the effect of humidity, microbes, pH, temperature, and wind can be engineered by wrapping it by functional clothing. In this regard, the latest class of textile material has been added called functional textiles. Such clothing materials consist of the potential of delivering more than one functionality apart from its primary function to cover-ups the human body. This present chapter offers state-of-the-art viewpoints on the application of functional textiles, including assorted concerns. First, the skin responds to various environmental stimuli and then overviews various techniques to incorporate functionalities in textiles. Finally, the applications and future scope and possibilities of research in this field are included in this chapter. Miniaturisation to small micro to nanometre scale is registered as one of the most exciting meadows in engineering and science over the past few decades. This drift also grasps colossal potential to functionalise the textiles. Various techniques are available now to develop a thin uniform film of functional materials on clothing surface to offer extra functionalities hitherto unrevealed to textile processors. These technologies are based on layer-by-layer assembling, immobilisation of enzymes on textile surfaces, nanocoating of textile substances, plasma for nanoscale modifications, and loading of various functional biomaterials micro and nanoencapsulation by minimum influence on breathability, feel, handle, and strength. The manufacturing of functional textiles can be classified into two groups. One is to functionalise the fibre by adding dope additives, modifying the fibre forming polymer, and then converting it to clothing. The fibre surface is also functionalised by adding some resins on the fibre surface. The other is to modify the textile surfaces by functional biomaterials, resins, finishes.

Keywords: cosmetic textiles, skin care, skin moisturising, active textiles, microencapsulation, natural dyes, smart textile, enzyme immobilisation, wellness textiles

1. Introduction

The functionalisation of different surfaces is of curiosity since the chronicle emergence of various technologies in the antiquity. Different surface coatings and painting materials and techniques were developed to alter the aesthetic

appearance, functional potential, and protection against the environment like resistance against oxidants [1, 2].

Initially, durability was prime criteria for selecting any fabric by the customer in the ancient era, and then aesthetic values and comfort index were primary attributes to decide the fabric choice. Now, customer's approach about clothing and textiles is shifting to search some additional functionality apart from traditional attributes in textiles. The functionality may come from protective clothing, cosmetotextiles, and temperature regulating textiles, industrial textiles, sports textiles, and automotive textiles. All the above textile materials must keep at least any one specific functionality to register as functional textiles.

The functional textiles market is growing with an excellent growth rate of 33.58% between 2015 to 2020. The global functional textile market was reached 4.72 billion US$ by 2020. India is a prime manufacturer in apparel and textile manufacturing and fourth-largest exporter in the international sector.

The functional textile sector has encountered a compound annual growth rate (CAGR) of 30% from 2015 to 2020 due to strong automotive, fitness, fashion, healthcare, military, and sports textiles.

The physical finishing process includes three methods: impregnation, padding, and coating, and its main drawback are that the bonding force is weak between the finishing agent and textiles. However, its strength is more durable, and functionality can be maintained for a long time. The chemical finishing method involves grafting a functional monomer onto a polymer substrate, to obtain a new functional textile. The advantage is that its functionality can be maintained for a long time. Biological, ecological finishing is a finishing method which has emerged in recent years, and it adopts biological enzymes with biological activity in the finishing of textiles.

Smart textiles do not necessarily imply a less sustainable option to ordinary textiles if they offer better user value, user attachment and longevity. This chapter discusses the difference between ordinary sustainable methods based on saving energy and resources and methods that tackle excessive consumption, such as user involved design to enhance product durability. It discusses the theoretical model of user involved design through a practical example of developing a smart, lightweight tracking tent and concludes with a set of general guidelines for developing sustainable smart- textile products.

The functional textiles can be defined as textiles consist of additional functions of adjusting and regulating various attributes like temperature, humidity, colour and controlled release of some additives from fibres. The most popular fibres used to manufacture various types of functional textiles are polyester and viscose. Other fibres are also used to manufacture functional textiles as the need for some specific functions. The significant demand for functional textiles arises from active and high-performance wear sectors.

Some leading manufacturer of functional textiles at the international horizon are Dyntex GmbH, Eclat Textile Corporation Ltd., Harvest SPF Textile Company Ltd., Kelheim Fibres GmbH, Sofileta, Trevira GmbH, Toung Loong Textile MFG.

2. Classification of functional textiles

Various authors and researchers have tried to classify the functional textiles on their own time, but it is not easy to propose an ideal classification [3].

Functional textiles have become instrumental for the advancement of the conventional technical textiles segment, representing a sector where traditional clothing crosses the usual frontiers and connects with the spheres of biotechnology, cosmetic science, computing potentials, flexible electronics, medicine, and

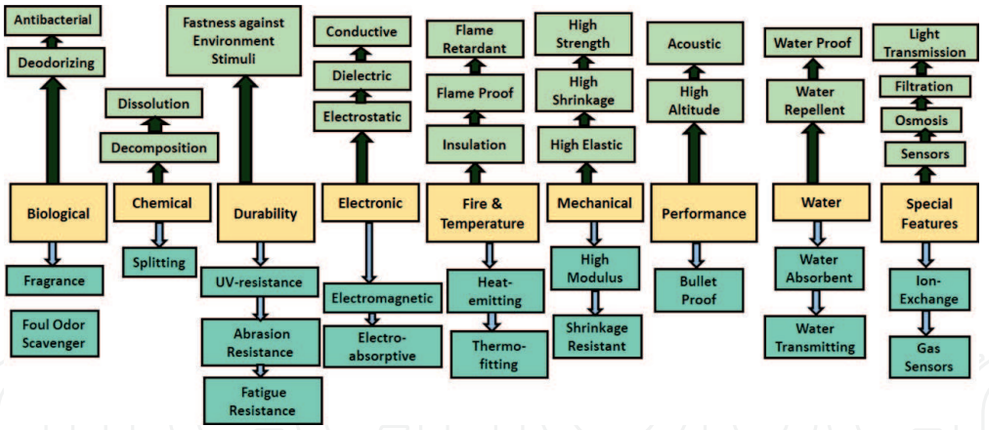

Figure 1.
Various stimuli and their corresponding functionalities for textiles.

nanotechnology among some more, to achieve the multidimensional and complex demands of the customers. By definition, Functional textiles are user-governed specified and customised or engineered products manufactured to fulfil the customer's performance needs under extreme conditions.

Gupta [3] classified the functional textiles logically in six categories. Now including three more, present classifications consist of nine different functional classes, as shown in **Figure 1**. It is essential to clarify that some more classes will introduce functional textiles classification as per the demand and availability of various functional textiles shortly. There is a slight difference between functional and technical textiles. All functional textiles may belong to technical textiles, but all technical textiles may not be functional. For example, protective functional textiles may belong to protective surgical masks for doctors, healthcare workers, and sports armour.

3. Functional textile market

The aerothermal concept has been adopted in functional textiles to control the heat containing airflow through fabrics. These functional textiles are manufactured and marketed by Adidas, and Peak Performance of the IC group. The Schoeller Technologies AG developed far infrared-based functional textiles' Energear' to collect the energy employed by the human body. Remarkable developments and innovations polymer and fibre science, coating and finishing technologies are the major driving forces for the growth of functional textiles. The initial demand for functional textiles was originated from various sports wear used in cycling, ski sports, swimming. The latest development in functional textiles turned the customer highly demanding for functional textiles. The higher cost of functional textiles stamped it textiles of premium class. Thus, the challenge of cost reduction in functional textiles manufacturing chain is the need for the present era to make it available for the common man and accelerate functional textiles' global market. Geographically, the functional textiles market is divided into five regions the Asia Pacific, Middle East and Africa, European Union, Latin America, United States of America. European Union secured the first position in manufacturing Functional Textiles mainly in Germany, France, Italy, and the United Kingdom. The USA also has a healthy manufacturing and market for functional textiles.

The Asia Pacific and Middle East Africa have the immense opportunity to grow the functional textile market. Japan, Malaysia, South Korea, Turkey, and Taiwan are predicted to be a promising market for functional textiles. The maximum number of functional textiles is manufactured by the application of various finishing agents

on textiles. Thus, the international market for finishing agents is expected to grow to 4.52 billion US$ by 2025. The protective textile segment, including health care and protection, is an up-and-coming field of functional textile is anticipated to manoeuvre the market rise in the next years. Enhancing buying potential and expendable income in emerging countries like Brazil, China, India, Russia, Taiwan, and Indonesia is another driving force of the growth of the functional textile market. However, the strict regulatory norms to restrict harmful and toxic chemicals will remain the requisite provocation for functional textile manufactures.

Functional textile finishing agents are dominated by various repellant and release agents in recent years and expected to grow with CAGR of 4.8% till 2028. The application of flame retardant chemicals was 22% of global textile finishing chemicals in the year 2020.

The major functional finishing agent manufacturers are Archroma, BASF SE, Covestro, CHT Group, Evonik Industries, Huntsman Corporation, Sumitomo Chemicals, Dow Chemical Company, HT Fine Chemical, FCL, KAPP-CHEMIE, NICCA CHEMICAL CO., Ltd., OMNOVA Solutions, Tanatex Chemicals B.V., Wacker Chemie AG, Zydex Industries, Sarex and others.

4. Functionality in textiles

4.1 Functionality by micro and nano encapsulation

A technique in which an active substance is stored in tiny space covered or coated with a thin polymeric material to protect the core material along with controlled release, is called microencapsulation.

Particles obtained by this process are called microparticles, microcapsules and microspheres according to their morphologies and internal structure. For particles with a size range below one μm, the terms 'nanoparticles', 'nanocapsules' and 'nanospheres' are used, respectively. Furthermore, particles larger than 1000 μm are designed as microcapsules. The nomenclature used to define different parts of the encapsulated product includes terms for the shell, ie, 'wall', 'coating', 'membrane material'; and for the core material, ie, 'active agent', 'payload', 'internal phase', respectively. Different kinds of compounds such as dye, protein, fragrance, monomers, the catalyst can be encapsulated with various shell wall materials like natural polymer (gelatine, cellulose, chitosan, etc.), artificial polymers (cellulosic derivatives, etc.) and synthetic polymers (polyamide, polyester, etc.), with a loading content between 5% and 90% of the microparticles in weight (**Figure 2**).

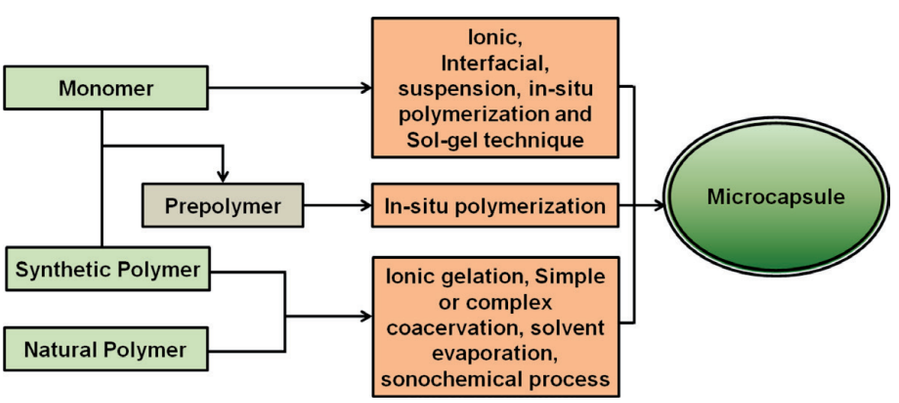

Figure 2.
Functionality by microencapsulation.

Sheath polymer	Core active material	Function	Reference
Poly (urea urethane) PUU	Sensitive dye	To get colour as a function of time	[4]
Poly (urea urethane) PUU	Cooling agent	To get cool feel during wearing	Salaün et al. [5]
Poly (urea urethane) PUU	Fragrances	To get controlled fragrance release	Teixeira et al. [6]
Poly urethane/ polyurea	Antimicrobial	To get bacterial protection	
Polyurea	Flame retardant	To get improved flame protection	[7], and Vroman et al. [8]
Polyurethane/chotopsan	Thermochromic	Colour change as a function of temperature	Fan et al. [9]
Cellulose derivative/PU	Phase change materials	To control environmental temperature flactuation	Salaün et al. [10]
Polyurethane	Cosmetic Ingradient	To get skin care functionality	Azizi and Chevalier [11]

Table 1.
Microencapsulation by interfacial polymerisation.

Micro and Nanoencapsulation is a technique in which a thin wall surrounds a tiny amount of active ingredient or droplets. The capsule wall's active material is called core material while the coating material is known as shell or membrane. Microcapsules have a diameter of few microns whereas nanocapsules have diameters of some hundreds of nanometres. Micro and nanoencapsulation is an up-and-coming technology to functionalise the textiles by potential core material for desires functionality. Micro and nanoencapsulation have permitted biocides, insecticides, essential oils, moisturisers, energisers, moisturisers, therapeutic oils, and vitamin E to be uploaded into fabrics. Some other applications are agrotextiles, cosmetics, industrial textiles, food additives, essences, herbicides, nutraceuticals, and sealants. The microencapsulation by interfacial polymerisation is given in **Table 1**.

4.2 Chemical grafting

The traditional binder application binds some functional compound on textile surfaces and creates a three-dimensional network and starts hindering the release of functional ingredient from the surface. The absence of strong chemical linkage between the capsule sheath and substrate surface exhibits inferior wash fastness and low air and moisture transmission. During pad-dry-cure, some of the capsules get burst due to the presence of applied pressure on substrate. Microcapsules are covalently connected onto textile surfaces by opting multifunctional crosslinking (coupling) reagents to enhance the fastness against wash and wear.

Microcapsules with ethylcellulose sheath are grafted on cotton fabric surface using 1,2,3,4-butane tetracarboxylic acid as crosslinking agents that react with a hydroxyl group cellulose to configure ester bonds [12].

Dimethyloldihydroxyethylene urea was opted as a coupling agent between chitosan and cellulose to form a covalent bond to enhance washing fastness [13].

Citric acid was another choice to crosslink chitosan microcapsules on cellulosic surfaces [9, 14].

Grafting strategies from the particle surface modification can be performed by introducing reactive chemical groups like α-Bromo-acrylic acid, adipic acid, 2,4,6-trichlorotriazine and dichloroquinoxaline, to react with the microcapsule sheath materials to offer further grafting possibilities onto natural, manmade fibres. Polyamide capsules and silica microspheres with 2,4,6-triochlorotriazine were functionalised to be deposited on cotton fibre surface [15].

Microcapsules were dispersed in water and glycidyl methacrylate monomer, and potassium persulfate was added to initiate an outer shell of poly(glycidyl methacrylate). The microcapsules were then applied by exhaustion in alkali medium to jersey cotton knitwear with a liquor ratio of 1:10 at 75 °C for 30 min. After rinsing, the sample was dried at 120 °C. The functional groups of the poly(glycidyl methacrylate) on the outer surface of the microcapsules are directly reacted with the functional groups of the fibres, which also conveyed durability of the PCM microcapsule-incorporated fabric even when subjected to physical processes involving frictional forces, or chemical processes such as domestic and industrial washing, or dry cleaning [16]. Gouveia used a sonication method to produce and simultaneously bind the microspheres onto textile materials [17].

Polyamide microcapsules are directly synthesised on cellulosic surfaces with 80% high encapsulation [18].

4.3 Functionality by layer by layer (LbL) deposition

Some studies were planned to modify the textile surfaces through layer by layer deposition to get nanocomposite textile fibre and protective clothing. Various functional molecules like enzymes, dyes and charged nanoparticles are deposited on textile surfaces in a controlled manner. Various finishing processes are based on Ag, TiO2, Zn nanoparticles to functionalised various textile surfaces [19]. Layer by layer deposition technique is a distinctive technique invented to develop ultrathin composite films on the surface of solid materials. A series of layer-by-layer deposition of polyanions and polycations on oppositely charged surfaces occurs in this method [20].

This process involves the charging of substrate sufficiently, followed by dipping in a conversely charged polyelectrolyte. The process begins by charging a substrate appropriately, followed by immersion in an oppositely charged polyelectrolyte solution and rinsing. Strong electrostatic bonds between charged surface and polyelectrolyte become the main instrumental in getting it to bind. The process begins with rinsing followed by monolayer coating of polyelectrolyte which gets bind by electrostatic bonds and process may repeat to be deposited 20 ultrathin layers [21–23].

Unlike pad-dry-cure, radiation, and thermal deposition methods, different finishing techniques are used to deposit various nanoparticles on textile substrates. The chemical coating on textile surfaces has some limitations due to higher thickness, which suppresses textiles' breathability. The LbL technology offers moderate chemical deposited surfaces to keep transmission, thickness and stability up to the desired extent. Various textile surfaces are modified by LbL technique.

Cotton, Kevlar, Nylon, Nomex, Silk and Wool fabrics were opted to functionalised for different applications by platinum atomic layer deposition. The platinum layer by layer deposition on textile surfaces was targeted to fabricate resistive heating devices with high stability and long life. The platinum deposition was found uniform layer by layer except for nylon fabric surface. [(1,2,5,6-η)-1,5-Hexadiene]-dimethyl-platinum(II) (HDMP; Tanaka Kikinzoku Kogyo K.K., Japan) and O2 gas were used as a Pt precursor and counter-reactant, respectively. The substrate temperature was maintained at 145 °C during the ALD process. Field emission scanning electron microscope integrated with energy dispersive spectroscopy (EDS) was

used for quantitative and elemental deposition conformation on textile surfaces. The atomic-scale crystalline and chemical structures of treated fabric specimen were analysed opting transmission electron microscopy (TEM) and electron energy loss spectroscopy (EELS), respectively [24].

Lee et al. [25] developed a pressure sensor atomic layer deposition on the cotton surface by depositing [(1,2,5,6-η)-1,5-hexadiene]-dimethyl-platinum(II) (HDMP) and O2 as the Pt precursor and counter reactant. The research group developed a useful atomic layer deposition technique. The deposition process may repeatedly apply up to 10,000 times. This technique helps produce various E-textiles by combining and connecting the number of sensors in a textile item that may be proved as propitious applicants for a range of smart and wearable electronics.

Stawski et al. [26–28] deposited oppositely charged polyelectrolytes; poly(acrylic acid) and poly(allylamine hydrochloride) layer-by-layer on a polypropylene knitted fabric, which had areal density 80 g/m2, diameter per filament 14.9, 18 courses per centimetre, 14 wales per centimetre, 56 dtex multifilament yarn.

The polypropylene (PP) fabric was activated as per the protocol opted by Połowiński [29] and [30–32] by heat-treating the fabric samples in an aqueous solution (20 g/L) of ammonium persulfate for 30 minute at 80 °C, and saturated with nitrogen), rinsing thoroughly with distilled water, and grafting with concentrated acrylic acid (52 g/L) for 60 minutes at 80 °C, saturated with nitrogen. After completing the grafting process, the PP fabric samples were dipped in an aqueous polyelectrolyte solution (10–2 mol/L). This process may repeat many times as per the need of desired end applications. Before initiating a new layer, deposition fabric specimens were rinsed with distilled water. In this way number of polyelectrolyte layers was coated on PP fabric surface [28, 29]. The PP samples functionalised by LbL technique were found to significantly reduced the static charge half-disappearing time, from 46 to 5.7 minutes. The degradation temperature shifted from 330 to 420 °C. The capillary rise has increased from 50 to 400 mm in the case of surface-modified knitted fabric samples. SEM and wide-angle X-ray diffraction was used to confirm the layer by layer deposition on PP fibre surface. It was found that the layer-by-layer deposition of polyelectrolyte considerably modifies dyeability, electrostatic shielding potential, and hydrophilicity of PP fabric samples.

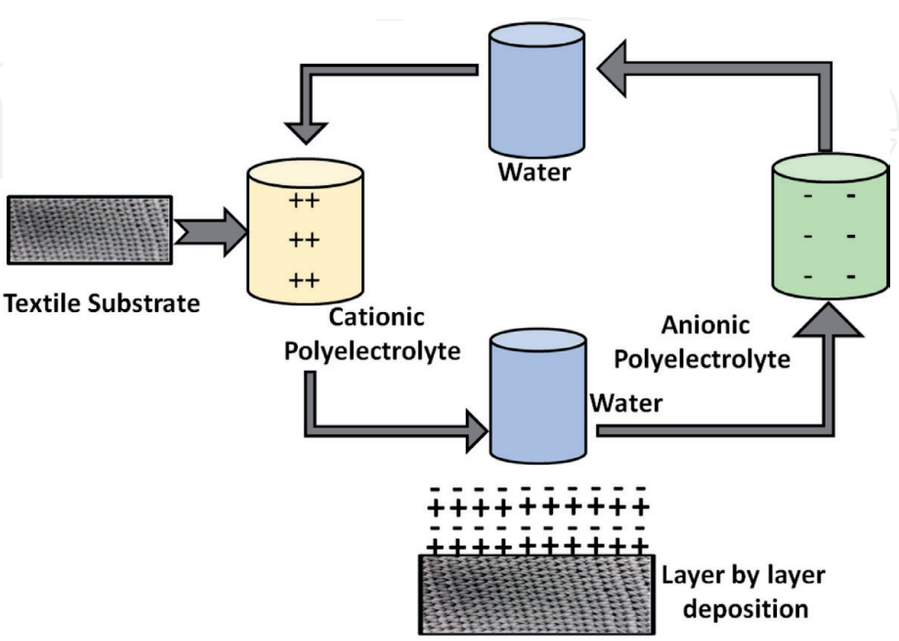

Figure 3.
Concept of layer by layer (LbL) Technology for Functional Textiles.

Highly durable hydrophobic polyester fabric surfaces were created by LbL nanoparticle coating on the fabric surface. Electrophoretic deposition (EPD) technique was used to modify the fabric surface with deposition of silica nanoparticles. The deposition of silica nanoparticles remains challenging on non-conductive surfaces like polyester due to undue cracks and poor adhesion. Thus electrostatic self-assembly layer-by-layer technique was opted to overcome these issues as shown in **Figure 3**. The polyester fabric modified by LbL silica NPs deposition offers a very high contact angle in static condition along with low contact angle hysteresis. The superhydrophobicity was remained intact ever after 500 h skin fiction [33]. This method provides fast and customisable deposition of superhydrophobic surface coatings. The coating thickness can be controlled by the electric field intensity and deposition time. Furthermore, the modified surface's morphology can be altered by changing the suspension stability during EPD [34]. Three significant routes achieve sustainable surface functionalisation; by alternating a charged substrate's immersion in aqueous solutions containing interacting charged particles, chemical vapour deposition, and spraying the interactive solutions on charges surfaces.

4.4 Functionalisation by fabric engineering

Fabric Comfort, good low-stress mechanical properties, pleasant aesthetic appeal, elasticity and recovery, favourable formability, desired crease-resistance are some attributes can be achieved by fabric engineering. These attributes are required for various applications like formal wear, party wear, ladies wear and sportswear.

The PBT (polybutylene terephthalate), yarns have good elastic potential with high recovery after heat treatment, have been adopted to manufacture highly elastic cotton-like fabric. The effect of PBT elastic yarn, weave and fabric structure was observed on physical, elastic, UPF, comfort) properties of the fabric. PBT yarns have found it appropriate to introduce elasticity in selected areas of the fabrics. The fabric had quick-drying, easier folding and storage and perfect fit to all dimensions [35].

3D printing is another way to introduce various functionalities in a different range of textiles. 3D printing has opted in case of defence, protective, sports, flexible electronics and safety clothing.

3D printing is used to customise the product for specific applications. Various types of additives can be loaded on fabric surfaces as a part of printing inks or pastes. A variety of hard and soft flexible materials can be printed directly on the textile surfaces. A combination of additives can also incorporate some functionality on a common textile substrate by 3D printing. The effect of family of twill weave and different weft densities on adhesion potential of printed objects on polyester/cotton fabric surfaces was studied. A range of 3D objects was printed with polylactic acid (PLA) filament on textile surfaces. T - Peel adhesion test was conducted by Instron dynamometer. It was found that the 1/3 broken twill fabric has the maximum impact on the adhesion perspective [36].

The worldwide health consciousness has enhanced natural dyes' use to avoid the threat of allergy, mutagenicity, and carcinogenicity. Cotton fabric was dyed with an extract of fourty different plants with zero mordant. Some plants were able to record great wash and lightfastness like pomegranate peel and turmeric for yellow, madder and quince for yellow, indigo for blue, myrobalan for green, white onion peel and catechu for brown colour. White onion peel or turmeric dyed cotton fabrics have registered significant improvement in ultraviolet protection functionality [37].

4.5 Functional textiles by enzyme immobilisation

Enzyme driven textile functionalisation has attracted the attention of textile manufacturers worldwide. Nonpolluting, non-toxic, and biodegradable nature of enzymes make it appropriate for the green processing of textiles. The enzyme production can be enhanced commercially anytime as per the need in industry. Enzymatic bleaching, scouring, bio-washing, and bio-polishing cotton fabric have become quite popular in the textile industry. Recently cotton fabrics are modified through transesterification by Proteinase subtilisin enzymes. Woollen fabrics are made shrink-proof by transesterification by the use of proteinase subtilisin enzymes. The Laccase enzyme is used to functionalised the wool in multiple order with antibacterial, antioxidant and water repellant for grafting alkyl galettes. The hydrophilicity and antistatic charge potential are introduced in polyester fabrics by treating it with cutinases and esterases enzymes. The nylon and acrylic fabrics are functionalised by treatment with amidase and nitrilase. The functionalisation of textile surfaces is made by 'enzyme immobilisation' on textile surfaces to introduce some special functions to textile surface. The immobilised enzymes work better than free enzymes on the textile surface to impart long term functionalities on textile substrates. As compared to free enzymes, immobilised enzymes are permanently attached to the textile, thereby adding unique functionalities to its surface.

5. Functional materials

5.1 Phase-change materials

The micro and nanoencapsulation of phase change materials can alter the core material from solid to liquid and liquid to stable by changing the entropy within a specific temperature span. This technique is used to suppress the effect of temperature variation on the targeted subject. The encapsulation of phase change materials is used to keep the temperature of clothing at a constant level. Microencapsulated phase change materials enhance the comfort delivery of blankets, duvets, mattresses, snowsuits, and vests [38].

5.2 Fragrance finishes

Fragrance finishes are applied straight on textiles, but aroma stability lasts maximum up to a couple of wash cycles. The micro and nanoencapsulation of fragrances are used to prolong the fabric's aroma functionality for a much more extended period. This technique is mainly adopted to encapsulate various essential oil flavours like lavender, rosemary, pine and others on for aromatherapy to treat headaches, insomnia, and prevent bad odour.

5.3 Fire retardants

Encapsulation of flame retardant materials does not allow sacrificing the softness and other low-stress mechanical properties seeded by direct application of flame retardant chemicals. Scientific selection of core and sheath materials for flame retardancy can offer synergistic effect; organophosphorus compound as core and nitrogenous compound as a sheath. Some intumescent flame retardant coatings can also be generated by micro and nanoencapsulation technique. This flame retardancy technique is widely used in the military sector to treat the tentage, upholstery and firefighting dresses.

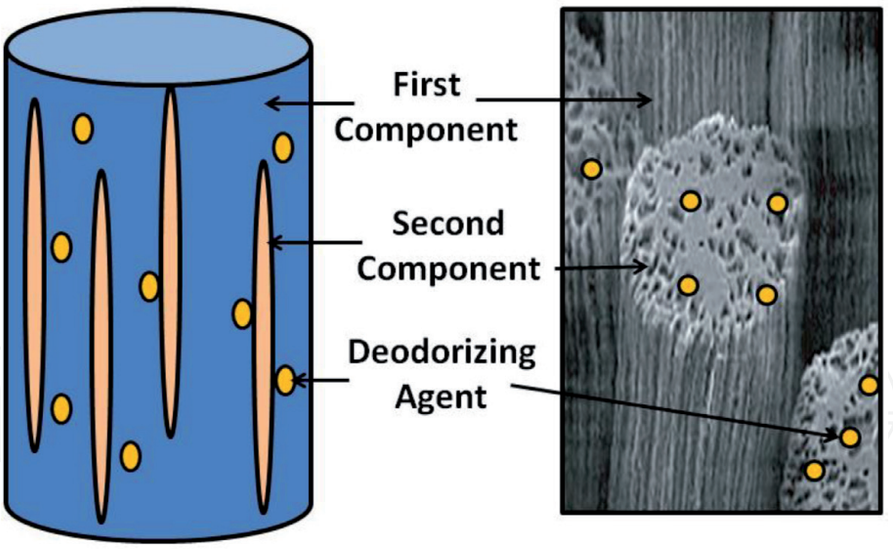

Figure 4.
Concept of inherent deodorant textile fibre.

5.4 Deodorant functional textiles

The deodorant fibres are manufactured by modifying the polymer molecular chain during polymerisation, by adding deodorant additives during fibre extrusion and by applying deodorant finish on fibre surface after spinning. The addition of deodorant additive as dope additive is simplest method to impart deodorancy in fibres as shown in **Figure 4**.

The polyester staple fibres were modified by photocatalyst and blended with cotton and bamboo fibre to produce several fabrics. The photocatalyst fibre contents were varied from 0 to 100% at a step of 20% increment in different samples. The deodorant potential of produced fabric samples was tested and examined. The conclusion is explained that as the photocatalyst fibre content reached 80% or 100%, the fabrics get better deodorant potential, but the photocatalyst content remains 40% to 60% in fabric samples, it shows low deodorant effect. It is established that at least 80% photocatalyst is essential to produce acceptable deodorant fabric [39, 40].

5.5 Polychromic microcapsules

The colours and dyes responsive against temperature are called as polychromic or thermochromatic dyes. The dyes and colours changes by a change in ultraviolet light are called as photochromatic dyes. The thermochromic or photochromic dyes are encapsulated inside the shell material used for product labelling, forensic purposes, and fashion applications. Many dyes and chemicals are available, which change colour by changing temperature and UV light exposure.

5.6 Antimicrobials

Microbes cause severe damage to various textile items. Some chemicals used to decay the microbial effects of fabrics are called as antimicrobials. These antimicrobials can be uploaded with textiles by microencapsulation technique in which antimicrobials remains in the core of the capsules. High-value textiles are treated by this method to prolong the life of these textiles.

5.7 Textiles for refreshing and relaxing

Refreshing and relaxing attributes are incorporated in textiles by uploading the *Aloe vera*, menthol, and essential oils with suitable emulsifiers in the capsule core. *Aloe vera* has found an appropriate finishing ingredient of textiles to achieve a refreshing and relaxing feel in textiles. These functional textiles are used to offer pleasant wear, wellness, and high energy levels.

Various plants and fruit-based aromas are also used by encapsulating and loading on fabrics for a functional point of view.

5.8 Textiles for cosmetics

A class of textiles responsible for imparting skincare, ageing combating, and wellness feeling is known as cosmetotextiles. Cosmetotextiles is one of the significant members of the functional textile family. The demand for cosmetotextiles increases every year due to the increase in self-wellbeing and purchasing power globally [41].

Cosmetotextiles are resultant of combining cosmetics and the textiles through different techniques, in which microencapsulation is the prime. Cosmetotextiles is a consumer textile product with a long lasting cosmetic ingredient released as a function of time.

5.9 Skincare functional textiles

Skincare is the most potent aspect of modern globally. The glowing skin is the desire of every person of the universe. The potential of skincare in textiles can be incorporated very easily by finishing the route. The functional textiles are capable of caring for human skin in various ways, and some are described here.

Skin soft 415 New:

This fabric finish is based on water-soluble phospholipid developed by Daiwa Chemical Inc., Japan. The finishing bath mainly consists of 2-methacryloyloxyethyl phosphorylcholine (MPC) with phosphatidylcholine polar groups to retain moisture on human skin for a long time [42]. A gentle softener is also used in Skinsoft 415 New to give a soft feeling to the wearer.

The skinsoft 415 finish has the potential to enhance the antibrowning and antistatic potential of textile surfaces [43].

Ohara Paragium Chemicals Kyoto, Japan, have floated a wide range of skincare and anti-ageing functional finishes to treat different fabrics. Some selected skincare finishes for textiles are;

- Parafine Skincare –1000: This finish was developed by Ohara Paragium Chem. Japan and that primly consists of silk-based amino acids. The amino acids are rich in moisture retaining properties that promote skin well-being by enhancing skin moisture.

- Parafine Skincare-3000: This finish offers cellulite reducing functionality by the presence of capsaicin, along with moisture-retaining and skincare effect by the presence of raspberry and squalane, respectively.

- Parafine Skincare-5000: The Parafine SC-5000 finish primly based on extracts of rice germ oil (ferulic acid and g -oryzanol) and vitamin E. The mixture

of ferulic acid, g –oryzanol and vitamin E offers anti-oxidation attributes to impart skin anti-ageing. This finish accelerates the anti-oxidation, blood circulation, and bio-membrane stabilisation in human skin.

- EVOTM Care Vital: This skincare finish recipe mostly contains *Aloe Vera*, Jojoba oil and Vitamin E to impart anti-ageing functionality in the finished fabric. This skincare finish was developed by Dystar Auxiliaries GmbH, Frankfurt, Germany. Some natural bio-substances are added with silicone matrix, which is an essential component of most softeners to enhance the washfastness of treated fabric surfaces. This finish is applied as the final treatment in the standard exhaust and pad-dry-cure process sequence. DyStar has introduced a similar finish with the commercial name of Evo Care BeeWell with beewax, Evo Care AVP and Evo Care AVS. Primarily, these finishes are based on *Aloe Vera* and Jojoba oil. Evo Care finish can finish a wide range of textile materials to impart anti-ageing functionality in innerwear that come directly in skin contact.

5.10 Insect repellent

The purpose of insect repellant functionality on textiles is to protect the wearer and cloth both from insects. The insect repellant materials are used to finish the traditional textile surfaces either by natural materials like (essential oils) such as citronella, eucalyptus, lemon, and neem or synthetic materials such as picaridin (1-piperidine carboxylic acid 2-[2-hydroxyethyl]-1-methlypropylester) or permethrin and (*N*,*N*-diethyl-3-methylbenzamide) (DEET). Direct application of these ingredients possesses very poor wash fastness. Thus most of them are applied through microencapsulation route by melamine–formaldehyde, sodium alginate, and silica as sheath material by pad-dry-cure method [44–47]. The efficacy of DEET was tested under laboratory conditions to inhibit blood feeding and killing mosquitoes for six months. This formulation was found very useful for mosquitoes got resistance against pyrethroid.

Textiles loaded with microcapsules containing citronella as the active ingredient has found better insect repellency (more than 90% for three weeks) than fabric sprayed with citronella oil and ethanol solution directly on fabric surfaces [48]. Lemongrass oil extract was uploaded on polyester fabric in microcapsule form and found 92% insect repellency. The mosquito-repellency was 80% when the polyester fabric was treated through pad-dry-cure route microcapsules containing methanolic lemongrass leaves extract as an active ingredient in capsule core.

5.11 Wellness

A cosmetotextile is a textile containing a substance or preparation targeted to be released permanently on different epidermis parts. It claims one or several unique properties such as cleansing, fragrance, skin appearance change, protection and upkeep, or foul body odour correction.

Some multinational companies like Oracle (France) and Dim launch fabrics with moisturising agent containing microcapsules grafted on textile surfaces. Global companies; Cognis in 2001 and Invista in 2003 floated their products as cosmetotextiles solution. Some other companies like Lytess (France), supplier for L'Oréal since 2009 with Mixa (2010), Mennen Garnier (2011), Biotherm, and then Nivea (2014) are continuously involved in this business. These companies are exclusively dedicated to the development and commercialisation of cosmetotextiles and have become a European market leader as a textile brand in this area. The Cosmetotextiles market was estimated at 500 million Euros in 2013, in which the slimming garments

contribute about 10% share. France is the first producer and consumer of cosmetotextiles, with 64% of the market in 2012. The development and manufacturing of new products will open new market opportunities, cosmetotextile manufacturers. Cosmetotextiles can be broadly divided into two major classes: (1) dermocosmetics (skin care) and (2) aromatherapy (release of essential oil and fragrances). Furthermore, a broad classification of cosmetotextiles is presented by Singh [49]. Grafting, padding, coating, spraying or screen printing are the major ways of applying microcapsules containing fragrance or cosmetic agents onto a textile [50].

5.12 Aromatherapy

Aromatherapy is considered an alternative route of medicine that uses volatile materials like essential oils by various peoples. Essential oil or fragrance is released from the microcapsule when any external stimuli actuate the fabric's microcapsule to promote the healing. The functional textiles for aromatherapy are found appropriate to affect the feelings, emotions and mood. Textile substrate works as a medium to deliver aroma conveniently at the desired moment. Various curtains, furnishings, handkerchiefs, and masks are treated with aroma finishes to incorporate functionalities. The microcapsules containing essential oils or fragrance are leaded on such textiles. Perfumed microcapsules are fixed on textile surfaces wither by the use of a binder or chemical grafting. Variety of essential oils like peppermint to get the exact thinking mood, lavender to get feeling of getting relax, similarly other oils for different purposes.

5.13 Photochromic textiles

Photochromic materials are uncoloured initially and do not absorbs light. These materials are activated only by high energy protons of ultraviolet rays present in the close surrounding of it. Organic substances like fulgides, spiropyrans, and spirooxanies are primly used as sensor in textiles.

For a textile application, organic compounds such as spiropyrans, spirooxanies and fulgides are mainly used to act as sensors [51]. The last category has found application in garments, toys and logos on T-shirts. Microencapsulation is used to improve the compounds' fatigue resistance as a result of deterioration after numerous repetitive cycles of irradiation and is affected by environmental factors [52, 53].

Photochromism is used in textiles to provide new functional smart fabrics such as garments capable of blocking UV radiation and sensing environmental changes, and also for aesthetics or functional effects such as camouflage, security printing, brand protection [51] and anticounterfeiting. Microencapsulated photochromic compounds can be applied by screen printing or grating onto a textile surface.

Di Credico et al. worked on a microencapsulation process to entrap a photochromic UV-sensitive dye dissolved in sunflower oil as a core material. After optimising the microcapsule shell's UV screening properties by tuning the core material's chemical composition, they demonstrated the use of such UV screening microcapsules in functional coatings for the nondestructive in situ visual detections of mechanical damage by colour change.

6. Benefits of functionalisation by microencapsulation

According to the desired functionality in textiles through microencapsulation route, microcapsules are planned and engineered. Nature of active ingredient core material, nature of sheath polymer, particle size, compatibility between core

and sheath material are some prime parameters that drive microencapsulation. Microcapsules with porous, semiporous or impermeable shells are used for different applications.

6.1 Protection and shelf life enhancement

Most of the active substances available are volatile, chemically fragile, or chemically, physically or thermally unstable, and cannot be applied directly on the textile substrate without being covered inside a shell. The micro or nano encapsulation not only provide the safety to the active substance from environmental stimuli; acidity, alkalinity, heat, moisture, oxidation) To restrict interaction with other chemicals remains present in the system to enhance the functionality delivery period.

The capsule shell is used to block the evaporation of active ingredients.

The capsules can also prevent the dissipation of volatile compounds. Additionally, the microcapsules save human resources at manufacturing and users side from exposure to harmful substances. Microcapsules allow safe handling of active ingredients before processing and permit a soluble substance to be transformed in a temporarily insoluble form. This technique permits an unpleasant fragrance from active compounds to be masked before end application during manufacture.

6.2 Controlled release

The microencapsulation of active substances is one of the best routes to enhance the efficiency and minimise environmental damage by controlled release.

This technology prolongs an active ingredient's delivery until an external stimulus like heat, moisture; pressure is actuated at a specific rate, time or situation. The microcapsules are desired to escape the core ingredient to the wearer under a range of controlled situations, which mainly depend on the choice of shell materials, the microencapsulation process opted and final applications.

6.3 Compatibility

The compatibility of core and shell material assists in microencapsulation. A binder's efficiency in connecting microcapsules to the textile surface depends on compatibility between various interphases of each component's microcapsules and finishing and chemical nature.

7. Microencapsulation technologies

The micro and nano encapsulation involve three necessary steps: enclosure of active ingredient as core material, the formation of microparticles and hardening. Again, these processes are further divided into three main groups depending on microparticles formation mechanisms. These three mechanisms are mechanical, chemical and physicochemical. The selection of one mechanism depends on various factors in which processing cost and selection of organic solvent is a significant point of considerations (**Table 2**).

Some multifunctional ingredients impart a range of functionalities on textiles after uniformly coating on it. Zinc oxide can introduce collective functionalities like antimicrobial activity, electrical conductivity, flame retardancy, hydrophobicity, moisture management, photocatalytic self-cleaning, and UV protection. In the development of wearable electronics, the enhancement of the piezo-photocatalytic activity of ZnO NRs by controlling the structure grown on conducting textile

Basic Ingredient	Functionality	Reference
Pro-vitamin C soluble in sebum	Cosmeto-clothing: Pro-vitamin C converts into vitamin C in the presence of sebum and is applied on blouses, and men and women's shirts	[54]
Aloe Vera, and Chitosan with other PCMs	Aloe Vera, and Chitosan with other PCMs Leg wear and intimate clothing for both men, women and Yoga Lines: Delivering cosmetic and well-being benefits like freshness, moisturising and massage for leg wear and intimate apparel. Stretch and recovery function through the use of Lycra	[49]
Distilled oils of plants, fruits and leaves	Textile has the functionality to provide gentle care to tired feet and legs with the special effects of invigorating aromas	[55]
Ultra-thin cloth with extracts of Padina Pavonica	The cosmetically inspired fluid lingerie "Hydrabra" provides moisturising and firming effects	[56]
Seersucker Woven Fabrics with Therapeutic Properties	Seersucker woven fabrics provide anti-cellulite functional knitted. The fabrics were measured in the range of their structural, mechanical, comfort-related and functional properties. These fabrics offer sufficient air transmission and good thermal resistance with gentle micro-messaging functionality	[57]
Chitosan microencapsulation with essential oils and bio-surfactants on cotton fabric	Smaller size microcapsules are obtained in presence of bio-surfactants. The antibacterial activity of fabric increases with the increase the add-on of chitosan and essential oil concentrations. The presence of essential oil decreases the stiffness but has no effect on wrinkle recovery	[58]
Deodorising Textiles	Photocatalyst modified polyester staple fibre, cotton, bamboo fibre, and photocatalyst modified polyester blended woven fabrics were offered good deodorancy at 80% or 100% photocatalyst fibre content.	[39, 40]
Wearable and textile electronics	Wearable and textile electronics was developed by thermal atomic layer deposition (ALD) at 300 °C with highly reactive counter reactants, including plasma radicals and O_3. High functional cotton fabrics are developed.	[25]
Temperature responsive functional textiles	A series of stimuli sensitive polymers were applied on various fabric surfaces to make them thermal responsive	[59]
Radar absorbers, microwave	Polypyrrole coated fabrics and fibres becomes able to absorb various waves sensitive in radar range	[60]
Camouflage electrochromic functional textiles	Polymers have a higher ion exchange capacity, higher hydrophilic/intensely coloured in the charged state are used to coat the textile surfaces. Coated textile colour is dramatically altered by application of small quantities.	[61]
Flexible wearable pressure sensitive textiles	Piezoresistive properties are incorporated to detect the loacal pressure on the fabric. These functional textiles become useful for injury prevention, rehabilitation, sports and medical applications	[62, 63]

Table 2.
Details of some selected functional ingredients, functions in functional textiles.

substrates will be crucial [64]. Silver nanoparticles and titanium dioxide nanoparticles functionalised Cotton-cellulose-spandex fabrics with various weaving configurations like plain, twill and satin with ester crosslinking agent, silicone

micro-emulsion. The treated fabric samples offered sufficient antibacterial, soft-handle, water/oil repellence, UV-protection and self-cleaning functionalities. The functionalised fabric samples retained these properties even after ten washing cycles [65]. Effective analytical techniques like scanning electron microscope with EDX confirmed the effective interaction between cellulosic surface and finishing nanoparticles.

The role of weave structure was also found crucial to enhance functionalities of treated fabric follows the descending sequence Satin (4) > Twill (2/2) > Plain (1/1) nevertheless of the used functional ingredients. The treated fabric samples showed bi-functional potentials like easy care-water and oil repellent, comfortable care-soft touch, or easy-care/antibacterial finish. The fabric finished with citric acid/NaH2PO2/TiO2-Nanoparticles to get easy care/antibacterial/anti-UV/Self-cleaning effect was stable regardless of fabric weaves.

The in-line characterisation of flame retardant and polyvinyl acetate based stiffed polyester and cotton fabrics were scanned by a hyperspectral camera (1320–1900 nm) based on chemometric approaches using the partial least squares (PLS) algorithm. The finish was applied to enhance the areal fabric density from 10–50 $g.m^{-2}$. For both the fabrics, the root mean square prediction error (RMSEP) was estimated at 1.5–2gm − 2. These results were found a very close correlation with gravimetry results also. The near-infrared imaging technique was also opted to detect the finishing agents' traces after washing the treated fabric surface. It was proved that a very thin layer of areal density between 0.4 and 5.5 g m − 2 was found intact even after many wash cycles [66].

8. Functional textile assessment

Functionality is a broad term used to assess the specific needs of clothing customers. The assessment of functional textiles primly depends on the satisfaction of the customer. Customer demands water-proof breathable fabrics, flame-retardant deodorant textiles, antimicrobial-perfumed textiles, soft-skin glowing textiles and others. Creativity, reliability, and aesthetics are three significant points of consideration during functional textile assessment planning. Some features must be considered as a part of the assessment is:

- Low-Stress mechanical properties
- Breathability
- Thermal Transmission
- Air transmission
- Presence of active ingredients on the fabric surface
- Colour Index
- Scavenging potential of foul odours and toxic gases

8.1 Low-stress mechanical properties

The alacrity desire for comfortable fabrics has become steering of the increasing demand for functional textiles. A dramatic shift in apparel goods has registered

from durability to functional aspect and increasing purchase power and customer awareness fueled it up. The rapid change in fashion trends and market demand has compelled the fabric manufacturer to follow the functional textiles design right from fibre manufacturing stage rather than relying upon experienced cloth manufacturing with conventional fibre design. The concept of high-quality apparel fabrics to achieve desired level appearance, handle and wearing comfort was finalised by Hand Evaluation Standardisation Committee (HESC).

Consumers'Consumers' purchasing decisions are usually based on feel fabrics for their tactile properties because, during daily wearing, low-stress mechanical action like bending, shear, compression, tensile, and hysteresis occurs on clothing. These common low-stress mechanical attributes significantly impact the feel, movement, sensory and tactile comfort. Other fabric and yarn properties like yarn counts; twist, coefficient of mass variation, neps, hairiness, thin and thick places, and strength and elongation also influence the clothing functionality.

Tactile properties of fabrics affect the functional aspect of apparel products and influence consumers' decision-making when purchasing textile clothing [67].

In the textile industry, tactile comfort is known as "handle" or in a broader sense "skin sensational wear comfort" or "sensorial comfort". Sensorial or tactile functionality, mostly identified by "hand or handle", is an inference of quantity of stress is generated in the fabric during use [68]. Tactile functional attributes are complex theories which incorporate dimensional alterations by small forces like bending, compression, shear, surface properties, and tensile. The feel of warmth and cool also influence the functionality of the fabrics.

Kawabata Evaluation system for fabrics (KES-FB) and Fabric Assurance by Simple Testing (FAST) systems are used to test the low-stress functional properties from a comfort point of view.

8.2 Breathability

The breathability of functional textiles is an essential parameter to be tested to assure the efficacy. The breathability of textiles is mostly referring to the moisture vapour transmission rate through the fabric. A series of instruments are available in the textile world, but moisture management tester of SDL Atlas is considered the prime instrument followed by some other concepts in which inverted cup method [69].

8.2.1 Sweating guarded hot plate tests

The sweating guarded hot plate's moisture vapour transmission resistance can be measured as per ISO 11092 testing standard [70]. This apparatus comprises the water supply unit and measuring unit in which the measuring unit is fixed with a metal block which consists of an appropriate heating element. The measuring unit is a permeable square metallic plate with area of 0.04 m2 and 3 mm. The specimen holder remains at the centre of heating plate which is surrounded by a guarded heating device. As shown in **Figure 5**, the guarded heating systems block any lateral heat escape from the samples' edges. The resist heater is fixed at the bottom of the heating plate to avert the descending heat loss from the specimen and guard section.

This positioning of various components operates heat or moisture transmission only upward along the specimen thickness direction. Distilled water is used to feed the surface of the porous plate through an appropriate dosing system. Water impermeable but water vapour permeable cellophane ultrathin membrane is fitted over the plate. The 300 X 300 mm2 sample is mounted over the membrane. The heating of square porous plate at the constant heating rate is started that mimics the

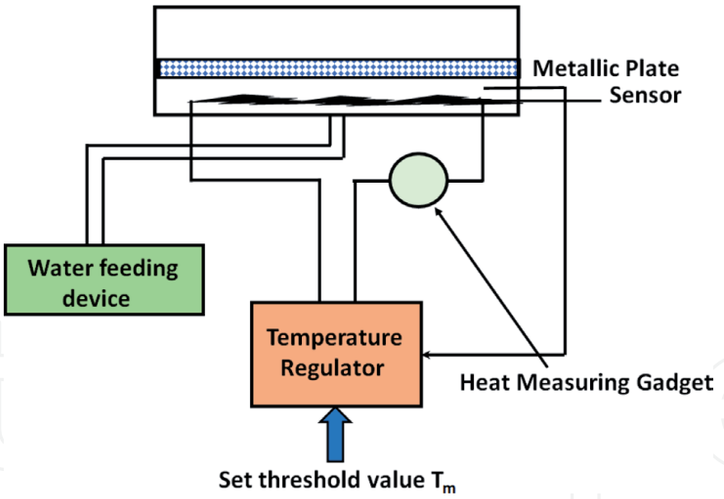

Figure 5.
Sweating guarded hot plate concept.

human body skin temperature, 35 °C, which is measured by a sandwiched sensor directly which is fixed underneath the plate surface. The entire system is closed in a chamber to control the micro-environment conditions very carefully. In order to simulate the actual condition, the air flow is kept at 1 m/s. The air temperature and relative humidity are maintained at 35 °C and 40% respectively.

8.2.2 Upright cup method

The water vapour transmission rates are measured as per ASTM E96, procedure B, and standard test methods by upright cup method. 100 ml distilled water is filled in a shallow cup and a specimen of size 74 mm is mounted on the cup by covering the gasket and fixing it in appropriate position. The cup and other accessories are housed inside an environmental chamber as shown in **Figure 6**. The temperature of circulating temperature is set to 23 °C with controlled relative humidity at 50%. The air flow is maintained with a velocity of 2.8 m/s. The cup assembly is

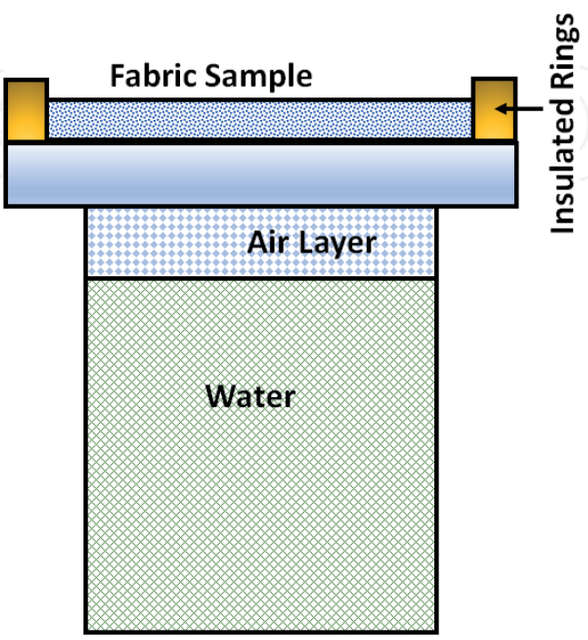

Figure 6.
Upright cup method.

weighed with accuracy of 0.001 g with the assistance of periodically top loading balance for 24 h. Finally the water vapour transmission rate is estimated by estimating the weight change g, in a time period of 24 h through a test area in m^2.

$$WVT = G \text{ X } 24 / t \text{ X } A \quad (1)$$

WVT = water vapour transmission rate, $g/m^2/day$.
G = weight change, g.
t = time during which G occurred, h.
A = test area, m^2.

8.3 Antimicrobial assessment of functional textiles

Assessment of antimicrobial functional textiles can be completed by testing the following attributes as summarised in **Table 3**:

Colour.

The antimicrobial finish application on textile surfaces should not alter the colour, which becomes the cause of significant quality deterioration. It is preferred to add an antimicrobial agent in dye bath if the dye and antimicrobial agent's chemistry allows for this.

Chemical Effects.

The antimicrobial agent must have zero chemical effects on the functional textiles. The tensile strength, elongation, bending rigidity, fullness and surface smoothness must be maintained for a long time.

Efficacy.

The efficacy of bacteriostatic/fungistatic or bactericidal/fungicidal treatments must be appropriately checked. Variety of chemicals is available to destroy the microbes, but their logical selection is required to prolong the fabric's functionality in a controlled manner. Apart from that, the antimicrobial agent should be effective at a relatively small quantity to control the add-on and cost of the material under permissible limits.

Odour.

The antimicrobial finishes should not release an annoying odour to the finished product, especially in apparel class. Many antimicrobial agents are prone to transmit unpleasant odour, while some are entirely free from foul odour feature.

Fastness.

The fastness or stability of antimicrobial finish is calculated in terms of resistance to abrasion, heat, light, laundering, oxidising agents, and ultraviolet rays. The deficient number of antimicrobial agents possesses all the above features. The antimicrobial molecule must be stable as a compound in a manufacturing environment. It should be steady not only for the finished functional textiles' purposeful life but also for the long storage period.

Hand.

The antimicrobial treatment of functional fabrics should not deteriorate the functional fabric's low-stress mechanical behaviour, particularly in the apparel sector's manufacture. The fabric should not attain a rough hand after antimicrobial treatment.

Toxicity.

The antimicrobial functional textiles must be free from toxicity or of a short order of toxicity. The antimicrobial potential is an essential feature for kids clothing where any type of toxicity is not permissible.

Test	Test Description and Expected Inferences
AATCC 100–2004 Antibacterial Finishes	The microorganism growth is completed in liquid culture, followed by dilution in a sterile nutritive solution. Inoculation is essential for sample and glassware. Bacteria quantity is examined at "time zero" by elution in a neutralising broth, followed by dilution and plating. A standard sample run is essential to confirm the neutralisation/ elution method effectiveness. Suppression of microorganisms reference to initial concentrations and the control sample is estimated. Percent reduction of bacteria R = 100 (B – A)/B where: R is % reduction A is the number of bacteria recovered from the inoculated treated test sample, B is the number of bacteria recovered from the jar immediately after inoculation (at "0" contact time)
AATTC Test Method 147–2004 Parallel Streak Method	Control and treated both samples are placed in close contact with the inoculated agar surface with test bacteria. A logical zone of heckled growth below and along the sample sides represents antibacterial potential of the fabric sample. A usual bacterial strain must use for test. The mean width of a zone of inhibition along a streak on either side of the sample is calculated by: W = (T - D)/2 where: W is width of zone of inhibition (mm), T is total diameter (mm) of sample and D is diameter of the test specimen in mm.
AATTC: 30–2004 Antifungal Activity of Textiles	This test method includes four methods for antifungal assessment on textiles. • One method involves testing fabric properties after burial in soil that contains fungi. • Second includes the cellulosic fabrics exposed to Chaetomium globosum in an agar plate and examination of subsequent growth. • The third method exposes textiles to Aspergillus niger in an agar plate and visually determines any fungal growth. • The fourth method uses a humidity jar to expose textiles to mixture of fungi spores. Any growth on the textile is visually determined.
AATCC TM30 Test IV	A dry, 1 × 3 inches strip of nutrient saturated treated and untreated fabric, sprayed with a mixed-spore suspension of mildew is suspended and incubated with sterile water in the standard moist conditions. The percent fungal growth is recorded after the incubation period. This test allows more clear differentiation between treated and untreated samples.
SN 195920	Determination of antimicrobial activity on textile fabrics: Agar diffusion plate test
SN 195921	Determination of antimycotic activity on textile fabrics: Agar diffusion plate test
SN 195924	Determination of the antibacterial activity on textile fabrics: Germ Count Method
JIS L 1902	Testing for antibacterial activity and efficacy on textile surfaces
ISO 20743	Testing for antibacterial activity and efficacy on textile surfaces
BS EN ISO 20645	Determination of antibacterial activity: Agar diffusion Plate test
BS EN ISO 11721-1	Determination of resistance of cellulose-containing textiles to micro-organisms- Soil Burial Test – Assessment of rot-retardant finishing
ASTM D 4300	Antimicrobial Testing for ability of adhesive Films to support or resist the growth of Fungi
ASTM E2149	Determining the Antimicrobial Activity of Immobilised Antimicrobial Agents under Dynamic Contact Conditions
ASTM E2180	Determining the activity of Incorporated Antimicrobial Agents in Polymeric or Hydrophobic Materials

Table 3.
Various tests for antimicrobial assessment [71–74].

9. Enzyme immobilisation for functionality on textiles

Various enzymes have been immobilised on various textiles surfaces, cotton, polyester wool, and flax, to achieve additional functionalities. Enzymes are biological catalytic materials used to keep up biochemical reactions by expediting the catalytic potential. Enzymes are proteins, which remains available in cells of living entities that are proficient in reducing the stimulation energy needed by chemical reactions in organic medium and living creatures [75]. The demand for enzyme application has been

triggered in all industrial segments, but the textile industry demands high performance, extremely stable enzyme at the uttermost pH and temperatures [76]. A physically attached enzyme on a water-insoluble surface, auxiliary material or carrier is called an immobilised enzyme [77]. These enzymes remain stable with the attached surface due to a proper linkage [78]. Various latest approaches appear regularly to immobilise various enzymes on surfaces to achieve improved efficiency, stability and applications. Many materials opted as carrier, substrate or support to immobilise the enzymes are inorganic, organic and organic synthetic carriers. Most inorganic carriers are aluminium oxide, activated carbon, bentonite, hydroxyapatite, kaolinite, nickel, titania, zirconia, silica gel, and glass. Inorganic carriers are less reactive with high stability and sound diffusion, and flowing potential. These carriers are very cost-effective also.

The organic carriers are mainly carbohydrates and proteins. The carbohydrate-based carriers are alginate, chitin chitosan, cellulose, dextran, and starch; however, the protein-based carriers are albumin, collagen, and keratin. These organic carriers offer little diffusion and flow potential. These organic carriers are effected easily by microbial contamination and pH.

Organic synthetic carriers are polyamide (PA), polypropylene (PP), polyvinyl, polyacrylate, polystyrene, copolymers of ethylene, polypeptides and polyaldehydes primly [79]. The organic synthetic carriers are appropriate for a wide range of enzymatic applications because they are not sensitive to microbial contamination [80].

9.1 Essential features for a substrate for enzyme immobilisation

The characteristics of immobilised enzymes are defined by the interaction between enzyme and substrate characteristics. Important characteristics to consider are the following.

Solubility.

The immobilised enzymatic system should be insoluble and rigid with the substrate surface to avoid biological contamination and enzymes' loss.

Functional groups.

The abundance, existence and activation of functionality are essential features of the matrix. These attributes are responsible for deciding the potential of the immobilised enzyme activity, stability under application situations. Generally, the immobilisation activity is performed via the nucleophilic reaction between the enzyme and substrate functional groups because the enzyme does not react with other organic reagents.

Dimensions and porosity/permeability

In general, the bigger the matrix surface area per mass unit, the greater the probability for the enzyme and substrate to get into contact. In terms of permeability, or porosity, the higher the porosity, the better the penetration of molecules between the enzyme and the substrate. Matrix pores bigger than 30 nm appear to support enzyme immobilisation by facilitating enzyme accessibility to the matrix's internal area [80].

Mechanical strength

This property takes importance depending on the reactor or the industrial vessel where the chemical reactions take place. When using immobilised enzymes in a stirring tank, the matrix is desired to be strong enough to prevent abrasion. Particle sizes lower than 50–100 μm may result in filters and sieve plugging.

Resistance to microbial contamination

The support material must be resistant and not affected by microbial attacks. It should be stable and inert to microbial contamination for an extended period.

Reuse

One of the benefits and thus a desirable feature of immobilised enzymes is their ability to be reused. This property makes them less expensive and compensative for

any extra cost than soluble enzymes, which is especially important when using an expensive matrix or support materials in some specific applications. Proper orientation of immobilised enzymes and support from crosslinking agents improves reusability.

Hydrophobicity and/or hydrophilicity

The hydrophobicity and/or hydrophilicity of the carrier, supporting material, or matrix is vital because such characteristics affect the strength and affinity of enzyme-carrier interactions noncovalent interactions [78]. This characteristic can also affect surface assimilation, dissemination, and obtainability of the product and substrate.

Matrix size and shape

These properties are significant for operating times. In general, the size and shape are dependent on the applications. Commercially, the matrix size can be available in the range of 150–700 μm particle size. A spherical shape matrix with a particle size range of 150–300 μm is preferred for stirred tank batch productions.

9.2 Enzyme immobilisation for textile processing

Different enzymes are tried to immobilise textile surfaces to achieve various functionalities, as summarised in Table.

9.2.1 Cellulases

Cellulase enzymes recorded global identity in textile processing due to their potential to functionalised the cellulosic fibres in a regulated fashion, manufacturing improved quality fabrics without significant compromise in structural damage [81]. Cellulases, a group of enzymes, can cause cellulose hydrolysis via β-(1–4) linkages degradation of the biopolymer, consequently releasing reduced sugars [82–84]. The cellulase enzyme's multicomponent tendency finds its most application in removing fluffy and protruding fibres from cotton fabrics (biopolishing) and for a stonewashed look in fabrics by efficient abrading of indigo-dyed denim [85]. A soluble–insoluble reversible polymer, Eudragit L-100, was successfully opted for cellulase immobilisation on cotton fabric surfaces and found an alternative to be used in bio-polishing and/or bio scouring of cotton fabrics [86].

9.2.2 Pectinases

Based on their mode of action, polygalacturonases degrade the complicated pectins found in plant tissues into simpler molecules like galacturonic acids [87, 88]. Pectinase has found its way in textile processing in the 21st century; otherwise, it was a known enzyme for the food industry [89]. Many non-cellulosic impurities are found in the primary wall of cellulosic fibres and less in the secondary wall, restricting the penetration of dyes and other functional finishes in the fibre interior [87]. The bioscouring of cotton is applied to degrade the cuticle and primary wall constituents from the cotton fibre surface to improve the hydrophilicity [90].

Pectinase immobilised on the cotton fabric surface for bioscouring in a reverse micellar system with pectinase dose of 10% (2.8 IU/g of the fabric) on the weight of the fabric at60 °C for 120 min, pH 7 to produce a hydrophilic fabric [91].

9.2.3 Amylases

Amylases are the enzymes, which split the starch molecules and starch related compounds in either exo or endo positions by hydrolysing α- 1,4- and/or α-1,6-glucosidic linkages in either endo- or exo-locations [92]. The removal of starch from warp threads of the fabric in which unsized weft yarn also remains present is safely possible by the amylase enzyme's selective action [93]. The immobilised amylases

Enzyme	Support System	Immobilisation	Benefits	Ref.
Amylase	Alkylamine glass beads coated with zirconia	Adsorption followed by GLUTAL	Immobilised enzymes with better washing fastness till 100 launderings without any considerable loss of activity	Dhingra et al. [94]
Cellulase	Polyvinyl alcohol coated chitosan beads,	Epichlorohydrin-Adsorption	Acid cellulase became a neutral cellulase	Dinçer and Telefoncu [82, 83]
	Chemically modified pumices particles	$ZrOCl_2$ - Adsorption	Gives stonewashed finish on indigo-dyed denim fabrics by efficient abrading	Pazarlioglu et al. [81]
Catalase	Alumina pellets	Covalent-GLUTAL	Higher stabilities and surfactant inactivation	Costa et al. [99]
	Alumina pellets	Covalent-GLUTAL	93% protein bound and 87% activity retained	Paar et al. [100]
	α- and γ-Alumina balls, Novalox saddles and Raschigrings	Covalent-GLUTAL	Higher porosity and shape of the carriers are two main parameters to influence the enzyme immobilisation stability.	Fruhwirth et al. [101]
	Cotton fabric or Nylon 6	Adsorption and covalent-GLUTAL	Low cost and flexible construction	Opwis et al. [102]
	Poly(ethylene terephthalate) or polyamide 6.6	Covalent -Photo chemical	After 20 application cycles, the immobilised enzyme showed an integral activity around 3.5 higher than free catalase	Opwis et al. [103, 104]
	Poly(ethylene terephthalate)	Chemical and Covalent-Photochemical	Enzyme modification before the immobilisation; photochemical technique may be able to compete with conventional immobilisation procedures	Opwis et al. [105]
Peroxidase	Polyethylene	Covalent-GLUTAL	Reusabilty was studied for 15 cycles and the half-life was found to be 60 h	Shaffiqu et al. [106]
Laccase	poly amide 6,6	Cross linking-GLUTAL and spacer	Potential for application in the continuous decolorisation of textile effluents, where it can be applied into a membrane reactor	Silva et al. [98]
Glucose oxidase	Cotton	Covalent binding	Recycling of desizing liquors into bleaching liquors	Opwis et al. [107]
	polypropylene	plasma activated, -OH Bond	To produce enzymatically active films, activity prolong upto 30 days of storage	[108]

Table 4.
Enzyme immobilisation on textile surfaces, (GLUTAL: Gluteraldehyde).

enzyme has opted in the detachment of starch and detergents from cotton fabrics. All detergents' performance enhances in the presence of immobilised amylase on cotton fabric surfaces [94].

9.2.4 Proteases

Proteases enzymes are used to carry out the protein degradation through hydrolysis of the peptide bonds in the polypeptide molecular chains [56, 95]. The traditional chlorination process in woollen fabric to achieve shrink-proofness causes ecological issues due to chlorine release is successfully replaced by immobilisation of proteases enzyme. The proteases action on woollen fabric enhances the dyeability, whiteness index and hand behaviour [96]. Some researchers have reported excessive damage in strength and weight loss in woollen fabrics [97]. Immobilisation of proteases enzyme on the textile surface typically enhances the molecular size, constraining proteolytic attack to the cuticle.

The modified protease is immobilised on the cuticle layer region to hydrolyse just the cuticle layer, producing higher tensile strength and a lower felting of the wool fibres. Silva et al. [98] used a commercial protease (Esperase) covalently linked to Eudragit S-100 as summarised in **Table 4**. This novel approach is a promising alternative for wool shrink-resist finishing, replacing the conventional chlorine treatments. Under optimised conditions (Eudragit, 2.5% w/v, carbodiimide, 0.2% w/v, coupling time 1 h and blocking agent concentration, 0.05%), the conjugate activity yield was about 45%, and its operational stability at 60 °C was increased by 1.7 times. Recently different enteric polymers are coupled with Esperase using carbodiimide coupling. More recently, Smith et al. [96] demonstrated that different enteric polymers could also be successfully coupled with Esperase using carbodiimide coupling on woollen fabric.

9.2.5 Glucose oxidase

Glucose oxidase is a dimeric glycosylated flavoprotein enzyme that can accelerate the oxidation of glucose to gluconolactone, which in turn, spontaneously yields gluconic acid as H_2O_2 as a side- product [109]. Therefore, glucose oxidase has been considered a possible method for producing H_2O_2 for green-bleaching, targeted at enhancing the fibre performance before colouration by tear down the pigments initially present in the natural fibres that possess greyness. Enzymatically produced H_2O_2 also gives a comparative bleaching effect with chemical bleaching. The immobilised.

9.2.6 Catalases

Catalases enzymes are known to cleave H_2O_2 into water and oxygen. H_2O_2 is a powerful bleaching agent and oxidises reactive dyes if H_2O_2 does not remove properly from cotton fabric [110]. Catalases enzyme cannot withstand commercial bleaching conditions like temperature 60 °C and pH 9 and above [111]. Alkalothermophilic and thermophilic microorganisms generated catalases enzyme is used as a successful alternative to commercial chemical bleaching. The immobilisation of catalase enzyme on fabric surface counters this issue and offers enzyme for re-application, saving energy and water both. Catalase immobilisation has been practiced by various researchers [109, 112, 113], with different carriers like organic and inorganic materials such as porous glass, cellulose, alumina, silica gel and hydrogels. Some biopolymers like gelatin and chitosan; additionally, some

synthetic polymers like polyacrylamide, were also used for bleaching treatments as summarised in **Table 4** [101]. In a remarkable work Kiehl et al. [114].

Opted catalase enzyme to immobilised on polyester, polyamide (Nylon 6, Nylon 66), cotton textile surfaces opting different strategies as mentioned in **Figure 7**. The catalase enzyme was loaded with 20–70 mg enzyme/g textile carrier to achieve reactivity upto 20% and excellent stability against enzyme desorption. The strategies like grafting, application of bifunctional coupling agents, monomeric and polymeric crosslinking agents were planned to achieve covalent fixation of the enzyme on textile carriers as shown in **Figure 7**.

9.3 Decolorisation of dyes and effluent treatment

9.3.1 Peroxidases

Peroxidases are oxidoreductases used to consume H_2O_2 to initiate the oxidation of a wide variety of organic and inorganic chemicals. Several studies covering general properties, biochemical and molecular characterisation, and industrial and environmental applications have been discussed and reviewed elsewhere [115–118].

The majority of the matrices currently used for the immobilisation of enzymes such silica, controlled pore glass, polyvinyl alcohol, polyacrylamide and chitosan beads were not suitable because of dye adsorption onto the matrices, probably inactivating the enzyme [106].

9.3.2 Laccases

Laccases enzymes are copper-containing oxidoreductases, which belong to the group of small blue oxidases. They are widely distributed in higher plants, fungi and bacteria [119, 120]. These enzymes are used to functionalised the various aromatic compounds (particularly phenols) and inorganic compounds, with concomitant reduction of oxygen to water. Laccases enzymes have found in various textile as well as other industries. The application laccase enzyme is expanding fast, decolourising textile effluents and bleaching textile substrates.

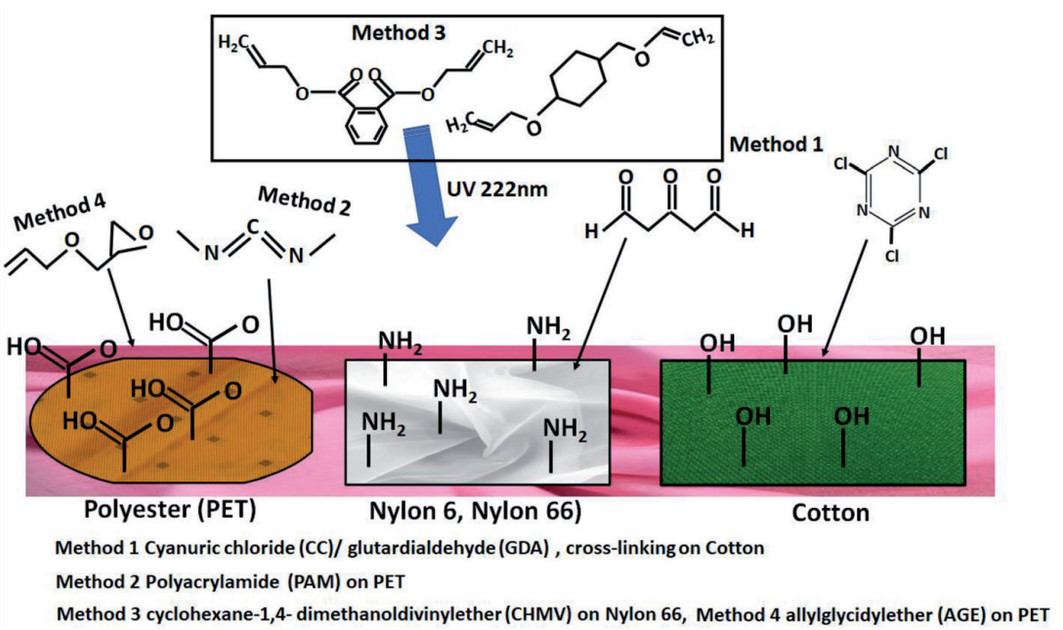

Figure 7.
Immobilisation of catalase enzyme on various textiles materials by different methods (Kiehl et al. [114]).

Most of the laccase enzymes are produced by white-rot fungi, which are efficient in decolourising dyeing effluents [121]. Research has shown that the subsequent coating of the alumina-immobilised laccase with polyelectrolyte layers considerably increased laccase stability.

In the initial stages of laccase action, decolorisation was primly due to the adsorption of the dyes molecules onto the support system, but the support enzymatic decolorisation was apparent after the saturation of support. Acid stable laccase enzyme works well in decolouration of low pH wool dyeing effluents with water recycling opportunity. Silva et al. [98] revealed the potential application of woven nylon 66 fabrics as a carrier for laccase immobilisation to be used in a membrane reactor.

10. Conclusions

Functional textiles are one of the most critical fields in the textile industry and textile materials science. They include breathable, heat and cold-resistant materials, ultra-strong fabrics (e.g., reinforcement for composites), new flame-retardant fabrics (e.g. intumescent materials), and optimisation of textile fabrics for acoustic properties. Functional textiles became more critical materials for various applications, and interest in them grew year by year.

Human skin offers the crucial first defence mechanism for the body to safeguard against external threats. Clothing fabrics and the human skin surface form a cushioning network that creates a thermal and sensorial state of comfort to keep a human being in the state of wellness.

The microencapsulation is the most versatile technique to impart various functionalities in textiles. Microencapsulation suppresses the compatibility between active ingredients and fibre surface by enhancing the functional durability, efficacy and sustainability. This technique's vast use can be witnessed in functional finish fabrics, medical and healthcare textiles, aromatherapy, cosmetic textiles, and many more functional textiles.

The moderate stability of these bio-catalysts primly restricts the immobilisation of enzymes on textile surfaces. The immobilisation of various enzymes on textile surfaces gives a sustainable solution of surface functionalisation for easy processing. Enzyme immobilisation twinning with other surface modifying techniques gives a synergistic effect in textile functionalisation. Various researchers are trying to enhance the temperature and pH range of enzymes for more effective immobilisation. The immobilisation allows the recovery of enzymes with increases stability to reduce the operation cost of different processes. Recent developments in the synthesis and fabrication of supporting materials with customised pore size and surface functionality have licenced more precise control of enzyme immobilisation. Perfectly oriented and highly rigid enzyme molecules are needed for better immobilisation and integration with different surfaces.

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References

[1] Lee D, Rubner M F, and Cohen R E (2006), Nano Letters, 6(10), 2305-2312

[2] Michel M, Toniazzo V, Ruch D, and Ball V (2012), ISRN Mat. Sci. 1-7

[3] Gupta D (2011), Ind J of Fib and Text Res. 36 (4), 321-326

[4] Chang C P, Yamamoto T , Kimura M, Sato T, Ichikawa K, Dobashi T, (2003) J of Contr. Rel. 86 (2-3) , 207-211

[5] Salaün F, Bedek G , Devaux E , Dupont D L, (2011b) J of Memb. Sci., 370 (1-2), 23-33

[6] Teixeira M A , Rodríguez O, Rodrigues S, Martins I, Rodrigues A E (2012), AlChE J, 58 (6), 1939-1950

[7] Giraud S, Rochery B M, Vroman I , Tighzert L, Delobel R, PoutchF (2005) Poly. Degra. and Stab. 88 (1), 106-113

[8] Vroman I, Giraud S, Salaün F, Bourbigot S (2010) Poly. Degr. and Stab., 95 (9), 1716-1720

[9] Fan F, Zhang W, Wang C (2015) Cellulose, 22 (2), 1427-1438

[10] Salaün F, Devaux E, Bourbigot S, Rumeau P (2010), Carbohydrate Poly. 79 (4), 964-974

[11] Azizi N, Chevalier Y, Majdoub M (2014) Isosorbide-based microcapsules for cosmetotextiles Industrial Crops and Products, 52 (0) (2014), pp. 150-157

[12] Badulescu R, Vivod V, Jausovec D, Voncina B (2008) , Carbohydrate Polymers, 71 (1), 85-91

[13] Liu J, Liu C, Liu Y, Chen M, Hu Y, Yang Z (2018), Colloids and Surfaces B: Biointerfaces, 109 (0), 103-108

[14] Yang Z, Zeng Z, Xiao Z, Ji H. (2014) Flav. and Frag. J, 29 (2), 114-120

[15] Cuevas J M, Gonzalo B, Rodríguez C, Domínguez A, Galán D, Loscertales I G, (2014) , J of Exp. Nanosci., 10 (11), 868-879

[16] Naylor RGJI, Magalhaes VVRM, Pinto CBS (2006), Microcapsules with Functional Reactive Groups for Binding to Fibres and Process of Application and Fixation, WO 2006117702 A2

[17] Gouveia I C (2012) , Poly. for Adv. Tech., 23 (3), 350-356

[18] Salaün F, Vroman I, Elmajid I (2012) Chem. Eng. J, 213 (0) (2012), pp. 78-87

[19] Kathirvelu S, D'Souza L & Dhurai B, (2009) Materials Sci, 15,

[20] Uğur S S, Sarıışık M, Aktaş A H, Uçar M C & Erden E (2010) Nanoscale Res Lett, 5, 1204

[21] Bertrand P, Jonas A, Laschewsky A & Legras A,(2000), Macromol Rapid Commun, 21. 319

[22] Lvov Y, Price R, Gaber B & Ichinose I, (2002), Coll Surf A Physicochem Eng, 375, 198

[23] Ou R, Zhang J, Deng Y & Ragauskas A J,(2007) J Appl Polym Sci, 102, 1987

[24] Oh K, Park J S, Khan M R, Kim K, Lee Z, Shong B, and Lee H (2019) Chem. of Mat. 31, 8995–9002

[25] Lee J, Yoon J, Kim H G, Kang S, et al., (2016), NPG Asia Materials, 8, e331, 1-8

[26] Stawski D, Zielinska D, Simon F, Polowinski S, Puchalski M (2014) Industria Textila 65 (4), 2-9

[27] Stawski D, Połowiński S (2011). In: Vlákna a Textil, 18 (1), 16

[28] Sánchez L S, Rodríguez J F, Carmona M, Romero A, Sánchez

P (2011) J of Appl. Poly. Sci., 120 (1), 291-297

[29] Połowiński, S (2007) In: J of Appl. Poly. Sci., 103(3), 1-7

[30] Stawski D, Bellmann C (2009 In: Colloids and Surfaces A: Physicochemical and Engineering Aspects, 345 (1-3), 191

[31] Stawski D, Halacheva S, Bellmann C, Simon F, Połowiński S, Price G (2011 In: Journal of Adhesion Science and Technology, 25 (13), 1481

[32] Stawski D, Połowiński S, Herczyńska L, Sarna E, Rabiej S (2012), 123 (3), 1340

[33] Joung Y S and Buie C R (2015), ACS Appl. Mat. & Interfaces, A-I

[34] Joung Y S, Buie C R (2011), Langmuir, 27, 4156-4163

[35] Kostajnšek K, Dimitrovski K, Kadoglu H, Çelik P, Bayraktar G B, Üte T B, Duran D, Ertekin M, Demšar A and Bizjak M, (2013), Polymers, 13, 260, 1-18

[36] Čuk M, Bizjak M, Muck D, Kočevar T N (2020) 3D Printing and Functionalisation of Textiles, DOI: 10.24867/GRID-2020-p561-4

[37] Karabulut K and Atav R (2020) Fib. and Poly., 21(8), 1773-1782

[38] Nelson G (2002), Int. J of Pharma. 242, 55-62

[39] Zhang H, Ge C, Zhu C, Li Y, Tian W, Cheng D, and Pan Z, (2012a), Physics Procedia 25, 240-244

[40] Zhang H, Ge C, Zhu C, Li Y, Tian W, Cheng D, Pan Z, (2012b) Physics Procedia 25, 240-244

[41] Singh M K, Varun V K, and Behera B K (2011) Cosmetotextiles: State of Art, Fib. & Text. in East. Euro. 19(4), 27-33

[42] Kanjana S, Nalankilli G (2018), J of Text. Eng. & Fash. Tech. 4(4), 316-318

[43] Nakamura S, Nishioka K, Otsuki T, (2010) Interview available at http://textileinfo.com/ en/chemicals/daiwa/01_06.html.

[44] Anitha R, Ramachandran T, Rajendran R, Mahalakshmi M (2011), Elixir Bio Physics, 40, 5196-5200

[45] Boh B, Kardos D (2003) Microcapsule patents and products: innovation and trend analysis R. Arshady, B. Boh (Eds.), Microspheres, Microcapsules and Liposomes, Citus Books, London, 47-83

[46] Chan ASC, Valle J del, Lao K , Malapit C, Chua M, So RC, (2009), Philippine Journal of Science, 138 (1), 13-21

[47] İnceboz T, Erkan G, Türkoğlu G C , Sarıışık A M, Bakırcı S , Üner S, Üner A (2015) , Text. Res. J, 85 (19), 2071-2082

[48] Specos M M, Garcia JJ, Tornesello J, Marino P, Vecchia MD, Tesoriero MV, Hermida LG (2010) Trans. of the Roy. Soc. of Trop. Medi. and Hyg., 104 (10), 653-658

[49] Singh M K (2005) "Sun protective clothing" Jan-Feb, 91-97

[50] Theberge K, Goudreault I, Quirion F, Perron G (2010) Articles of Manufacture Releasing an Active Ingredient, US 20100226947 A1

[51] Billah S M, Christie R, Morgan M (2008), Coloration Tech. 124, 229-233

[52] Fan F, Wang C (2014), J of Appl. Poly. Sci., 131 (20), 211-216

[53] Zhou Y, Yan Y, Du Y, Chen J, Hou X J (2013) Sensors and Actuators B: Chem., 188 (0) 502-512

[54] Fuji Spinning Co. Ltd Japan in European Patent EP 1 251202

[55] Tiwari D, Upmanyu N, Malik J and shukla S (2017), Int. J of Pharma & Chem. Res.3(4), 814-827

[56] Singh J, Batra N, Sobti RC (2001) Serine alkaline protease from a newly isolated *Bacillus* sp. SSR1. Process Biochem 36: 781-785

[57] Matusiak M, Wilk E, Zieliński J (2018) Seersucker Woven Fabrics with Therapeutic Properties, Fib. & Text. in East. Euro. 26, 5(131), 54-58.

[58] Javid A, Raza Z A, Hussain T, and Rehman A (2014) J Microencapsul, 31(5): 461-468

[59] Save N S, Jassal M, Agrawal A K, (2005) J. Appl. Polym. Sci., 95(3), 672-680

[60] Kuhn H H, Child A D & Kimbrell WC (1995) Synth. Met., 71, 2139-2142.

[61] Invernale M A, Ding Y & Sotzing G A, (2011) Coloration Tech., 3, 167-172

[62] Mazzoldi A, De Rossi D, Lorussi F, Scillingo EP & Paradiso R, (2002) AUTEX Res. J., 2, 199-204

[63] De Rossi D, Della Santa A & Mazzoldi A, (1999), Mater. Sci. Eng., C7, 31-37

[64] Verbic A, Gorjanc M and Simoncic B (2019) Recent Advances, Coatings 9 (550), 1-25

[65] Salaün F, Bedek G, Devaux E D (2011a) Mat. Lett., 65 (2), 381-384

[66] Mirschela G, Daikosa O, Scherzera T, Steckert C (2018) Near-infrared chemical imaging used for in-line analysis of functional finishes on textiles, Talanta

[67] Behera B K, Ishtiaque S M, and Chand S, (1997) J of Text. Inst., 88 (3), 255-264

[68] Behera B K, and Singh M K (2014), J of Text. Inst.,105 (4), 365-376

[69] ASTM E96 (1995) Standard Test Methods for Water Vapour Transmission of Materials, in. "Annual Book of ASTM Stand- ards 4.06". American Society for Testing and Materials, West Conshohocken, PA, 1995

[70] ISO 11092 (1993), "Textiles Physiological Effects Measurement of Thermal and Water Vapour Resistance under Steady state Conditions (Sweating Guarded Hot Plate Test)". International Organization for Standardization, Geneva, Switzerland (1993)

[71] AATCC Test Method 100-2004 (2012), Amer. Ass. of Text. Chem. and Colo., Res. Tria. Park, NC, 148-149

[72] AATTC Test Method 30-2004 (2012), Amer. Ass. of Text. Chem. and Colo., Res. Tria. Park,, NC., 80-82

[73] Shinde S (2010), Man-made Text. of Ind., July, 247-248

[74] Sathianarayanan MP, Bhat NV, Kokate SS, Walunj VE. (2010), Ind. J of Fib. and Text. Res., 35, 50-58

[75] Hettiarachchy N S, Feliz D J, Edwards J S, Horax R (2018) Protiens in Food Processing, 569-590

[76] Conesa A, Punt PJ, van del Hondel CA, (2002) J Biotechnol 93:143-158

[77] Bayindirli A, (1995) Immobilisation of enzymes and potential applications in food industry.

[78] Datta S, Christera L R, Rajaram YRS, (2013) Biotech. 3, 1-9.

[79] Costa SA, Azevedo H S, Reis R L, (2005) Enzyme immobilisation in biodegradable polymers for biomedical applications. Biodegradable Systems in Tissue Engineering and Regenerative

Medicine. CRC Press/Taylor & Francis Group/LLC, Boca Raton, FL. 301-324

[80] Tischer W, Wedekind F, (1999) Topics in Current Chemistry. 200. Springer-Verlag, Heidelberg, Germany, 95-126.

[81] Pazarlioglu NK, Sariisik M, Telefoncu A. (2005) Process Biochem 40, 767-771

[82] Dinçer A, Telefoncu A. (2006a), J Mol Catal B Enzymatic 45, 10-14

[83] Dinçer A, Telefoncu A. (2006b) J Mol Catal B Enzymatic 45:10-14

[84] Sinegani AAS, Emtiazi G, Shariatmadari H, (2005) J Colloid Interface Sci. 290:39-44

[85] Gusakov AV, Sinitsyn AP, Markov AV, Sinitsyna OA, Ankudimova NV, Berlin AG. (2001) J Biotechnol 87:83-90

[86] Dourado F, Bastos M, Mota M, Gama FM, (2002) J Biotechnol 99:121-131

[87] Hoondal GS, Tiwari RP, Tewari R, Dahiya N, Beg QK, (2002) Appl. Microbiol Biotech. 59:409-418

[88] Kashyap DR, Vohra PK, Chopra S, Tewari R. (2001) Bioresour Technol 77:215-227

[89] Gummadi SN, Panda T. (2003) Process Biochem 38:987-996

[90] Wang Q, Fan X, Hua Z, Gao W, Chen J. (2007) Carbohydr Polym 67:572-575

[91] Joshi M, Badhe P, Adivareker R, (2013) J of Mole. Cata. B: Enzymatic, 98 (12), 106-113

[92] Hamilton LM, Kelly CT, Fogarty WM, (2000) Enzyme Microb Technol 26:561-567

[93] Gupta R, Gigras P, Mohaptra H, Goswami VK, Chaulan B, (2003) Process Biochem 38:1599-1616

[94] Dhingra S, Khanna M, Pundir CS, (2006) Ind. J Chem Technol 13, 119-121

[95] Gupta R, Beg QK, Lorenz P. (2002) Appl. Micro- biol Biotechnol 59:15-32

[96] Smith E, Schroeder M, Guebitz G, Shen J, (2010) Enzyme Microb Technol 47:105-111

[97] Queiroga A C, Pintado M M, Malcata F X, (2007) Enzyme Microb Technol 40:1491-1495

[98] Silva C, Silva CJ, Zille A, Guebitz GM, Cavaco-Paulo A, (2007) Enzyme Microb Technol 41:867-875

[99] Costa SA, Tzanov T, Paar A, Gudelj M, Gübitz GM, Cavaco-Paulo A. (2001) Enzyme Microb Technol 28:815-819

[100] Paar A, Costa S, Tzanov T, Gudelj M, Robra K-H, Cavaco-Paulo A, Gübitz GM. (2001) J Biotechnol 89:147-153

[101] Fruhwirth GO, Paar A, Gudelj M, Cavaco-Paulo A, Robra K-H, Gübitz GM, (2002) Appl Microb Biotechnol 60:313-319

[102] Opwis K, Knittel D, Schollmeyer E. (2004) Biotechnol J 2:347-352.

[103] Opwis K, Knittel D, Bahners T, Schollmeyer E, (2005a) Eng Life Sci 1:63-67.

[104] Opwis K, Knittel D, Bahners T, Schollmeyer E, (2005b) Eng Life Sci 1:63-67

[105] Opwis K, Knittel D, Schollmeyer E, (2007) Biotechnol J 2:347-352

[106] Shaffiqu T S, Roy J J, Nair R A, Abraham T E, (2002) Appl Biochem Biotech. 102:315-326

[107] Opwis K, Knittel D, Kele A, Schollmeyer E, (1999) Starch 51:348-353

[108] Vartiainen, J.; Rättö, M.; Paulussen, S (2005) Packag. Tech. Sci., 18, 243-251

[109] Betancor L, López-Gallego F, Hidalgo A, Alonso-Morales N, Dellamora-Ortiz G, Guisán JM, Fernández-Lafuente R. (2006). J Biotechnol 121:284-289

[110] Thompson VS, Schaller KD, Apel WA, (2003) Biotechnol Prog 19:1292-1299

[111] Oluoch KR, Welander U, Andersson MM, Mulaa FJ, Mattiasson B, Hatti-Kaul R. (2006) Biocatal Biotransform 24:215-222

[112] Opwis K, Knittel D, Schollmeyer E. (2004b) AATCC Rev 4:25-28.

[113] Wang Y, Caruso F, (2005) Chem Mater 17:953-961

[114] Kiehl K, Straube T, Opwis K, Gutmann J S, (2015) Strategies for permanent immobilization of enzymes on textile carriers, Eng. Life Sci., 15, 622-626

[115] Atack JM, Kelly DJ (2006) Adv Microb Physiol 52:73-106

[116] Moreira PR, Bouillenne F, Almeida-Vara E, Malcata FX, Frère JM, Duarte JC (2006a) Enzyme Microb Technol 38:28-33

[117] Matto M, Husain Q, (2006) J Chem Technol Biotechnol 81:1316-1323

[118] Moreira PR, Bouillenne F, Almeida-Vara E, Malcata FX, Frère JM, Duarte JC (2006b) Enzyme Microb Technol 38:28-33

[119] Alexandre G, Zhulin I B, (2000) Trends Biotechnol 18, 41-42

[120] Duran N, Rosa MA, d'Annibale A, Gianfreda L (2002), Appl Catal B Environ 28:83-99

[121] Kandelbauer A, Maute O, Kessler RW, Erlacher A, Gübitz GM, (2004) Biotechnol Bioeng 87:552-563