Bio-based textile processing through the application of enzymes for environmental sustainability

Abstract

Textile industries contribute significantly to the economy of many developing countries. Every year, these countries export millions of dollars' worth of textile products to developed countries. However, textile industries use expensive and corrosive chemicals that pose a significant threat to environmental quality and public health. This has led to serious concerns and necessitated the inclusion of safer and environmentally friendly alternatives. Consequently, bio-based processing has created a new approach utilizing biotechnological advances. This article uses evidence from the scientific literature to examine the application of industrial biotechnology in textile-processing industries, which includes enzymes, as a sustainable alternative to the harsh toxic chemicals currently used in textile processing. The article draws on evidence that enzymes offer a competitive advantage over chemicals with less resource requirements (energy and water), reduced emission and less waste. Due to high specificity, enzymes produce minimum byproducts. The implementation of enzymes in textile processing could offer environmental benefits, and improve public health and the sustainability of textiles and apparel. This article contributes to critical awareness by providing succinct information about major enzymes used in textile processes to improve the performance of textile materials, thus contributing to changes in behaviours and attitudes towards textile processing and environmental sustainability. This can assist textile manufacturers and governments in the developing world in campaigns to promote biotechnologies for environmental sustainability.

Keywords

biotechnology

textile

enzyme

sustainable technology

environmental sustainability

developing countries

1. Introduction

Recent developments in industrial biotechnology have offered eco-friendly approaches without compromising production efficiency and product quality at industrial settings. Industrial biotechnology encompasses the use of enzymes and defined micro-organisms for goods and services (OECD 2001; Jørgensen et al. 2006). Enzymes are observed to have increasing applications in many industrial processes and have evolved into a multibillion-dollar business following the rapid growth of the global market for industrial enzymes (Sarmiento et al. 2015). Despite the presence of enzymes in all living entities, most of the enzymes in industrial use are of microbial origin. Industrial enzymes have found their applications in different sectors including leather, tanning, textile, pulp and paper, chemical and pharmaceutical, food, detergent and starch industries, among others (Li et al. 2012; Sarmiento et al. 2015).

Approximately 10 per cent of industrial enzymes account for textile processing (Silva et al. 2010; Choudhury 2014). Textile fibres and fabrics undergo a number of long production and manufacturing processes before they can be used for preparing garments or apparel. Textile-wet preparatory processes, which consist of scouring, bleaching, colouration and finishing, are carried out in water-based systems deemed indispensable for improving the performance and utility of textile materials (Kumar and Gunasundari 2018). Almost all dyes, specialty chemicals and finishing chemicals used in the textile applications are incorporated into the textile substrates from a water bath, either through solution, dispersion or emulsion. In textile-wet processing, water serves mainly two purposes: as a medium for handling and using chemicals and second, as a solvent for washing and rinsing the textile materials. The wet processing of textiles places a heavy burden on the use of water and energy. In addition, textile industries employ a variety of chemicals from the early stage of processing through to the stage of finished products. These chemicals are expensive and pose a significant threat to environmental quality, the ecosystem and aquifers, and to the health of manufacturing workers (Shen and Smith 2015; Saxena et al. 2017; Kumar and Gunasundari 2018). This has caused serious concern and necessitated the inclusion of safer and environmentally friendly, green alternatives. Consumer demand has heightened preference for sustainable textile materials and apparel (Gwozdz et al. 2017). Consequently, bio-based processing presents a significant potential for replacing harmful chemicals with materials requiring less water and energy, thus contributing to the production of sustainable textile materials (Maiti et al. 2018).

The textile and clothing industry is a major part of manufacturing and trade in many developing countries. These countries have taken advantage of the relative ease of entry into this field while high wages in developed countries have lost them the comparative advantage of the manufacturing and subsequent exportation of textiles and apparels. However, there is more to textile production than price-competitiveness. Concern with the issue of environmental sustainability and regulatory and policy regimes would impose stringent ecological constraints on textile processing that would not, however, compromise the quality-competitiveness of the final product. Biotechnological processes can, in this respect, contribute significantly to eco-friendly manufacturing by replacing traditional textile production systems.

This article addresses the following research questions: what is the scientific argument supporting the effectiveness of biotechnology in textile processing? To what extent can the use of biotechnology, particularly enzyme processing, bring about greener alternatives in textile industries? Based on the scientific literature, we discuss the benefits and issues associated with enzymatic processing with the aim of raising awareness among stakeholders about how biotechnology could help environmental sustainability in the developing world. In answering these research questions, we focus the analysis on five key biotechnologies in textile: bio-desizing, bio-scouring, bio-bleaching, bio-finishing and bio-stoning or denim bio-wash. The aim is to break complex scientific information into information that is intelligible to various stakeholders. The focus of the article on these five aspects is linked to the fact that they are novel, and information about them and their application is only emerging in the developing world.

2. Methodology

The article draws on relevant data and information from the existing body scientific literature to examine the potency of the use of enzymatic processing for environmental sustainability in the textile industry. This departs from the 'traditional hypothetico-deductive approach' to exploit the potency of secondary data in constructing a critical argument (Dana and Dana 2005). We first located the literature that addresses important developments in biotechnology that are geared to resolving some of the negative environmental impact of traditional processing in the textile industry. We then provided a discussion of the main findings supporting the use of enzymatic processing and biotechnology, categorizing the benefits but also dialectically establishing the issues associated with the use of biotechnology. Thus, our two-way approach expands 'the exploration of plausible rival hypotheses, process tracing and counterfactual reasoning' (Dana 2015:154.) in the debate about the use of biotechnology in enhancing the benefits associated with enzymatic treatment in textiles for environmental sustainability in developing countries.

3. Perspectives on enzymes in textile wet processing

Enzymes are biological catalysts that are responsible for performing specific chemical reactions. They usually require comparative mild conditions for their operation. All enzymes are proteins in nature and decompose after their lifetime (Shen and Smith 2015). Some enzymes require specific small non-protein molecules, known as cofactors, to function as catalysts. The reaction specificity of the enzymes could be used for targeted textile applications without undesirable effects (Shen 2009). Commercially enzymes are usually manufactured by fermentation from three primary sources: animal tissues, plants and microbes. Enzymes are classified as oxidoreductases, transferases, hydrolases, lyases, isomerases and ligases (Choudhury 2014). Most enzymes used in textile wet processing are hydrolases, which are responsible for catalysing hydrolysis of chemical bonds. This group comprises of amylases, cellulases, pectinases, catalases and proteases, which are used in various textile manufacturing processes. However, laccases and peroxidases belonging to the oxidoreductase group have found interesting textile applications that include decolourizing textile effluents, bleaching textiles, modification towards the surface of the fabrics and synthesis of dyes (Shen and Smith 2015). Specific enzymes, used alone or in combination with other enzymes for textile applications, are shown in Table 1.

TABLE 1 HERE…

3.1 Bio-desizing

De-sizing is a process that involves the removal of size from woven cotton fabric. The most common sizes are organic compounds such as starch and its derivatives, cellulose derivatives, polyacrylates and polyvinyl alcohol. Their role is to provide a protective coating on yarns during weaving. It is essential that after weaving, the size must be removed before dyeing and finishing. It is usually accomplished by treating the fabric with chemicals such as acids, bases or oxidizing agents (Aly et al. 2010). The de-sizing effluents contain high organics with Chemical Oxygen Demand (COD), which comprise approximately 60 per cent of the total organic load of effluents generated from the textile-processing industries (Parmar and Shukla 2016). Amylase enzymes are the major enzymes used for de-sizing in these industries and can be regarded as the main application of amylases for the enzymatic de-sizing processes or bio-desizing (Araujo et al. 2008;

Choudhury 2014). Based on the degradation mechanism, amylases are grouped into α-amylases (dextrinogenic) and β-amylases (saccharogenic). The α-amylases cleave at random locations on the starch molecule to produce maltose from amylose, or maltose and glucose from amylopection, while β-amylases produce maltose by a stepwise hydrolysis reaction. As α-amylases tend to be faster-acting than β-amylases and because of their ability to act anywhere on the substrate molecule, they are used for textile de-sizing (Regan 1962; Sojka-Ledakowicz et al. 2006; Hossain and Uddin 2011; Mojsov 2011). These enzymes catalyse the hydrolysis of water-insoluble starch to water-soluble end-products and could be easily removed from cotton in the subsequent washing steps (Opwis et al. 2010; Shahid et al. 2016).

The temperature requirement for de-sizing is usually at least 70°C, and higher temperatures are preferred (Shahid et al. 2016). A regular amaylase works at a temperature range of 25–55°C while medium-temperature-range amylases can be used in the range of 50–95°C. The availability of amylase preparations active at these temperatures has opened up the possibility of performing bio-desizing at temperatures higher than 70°C (Ando et al. 2002). Thermo-stable amylases can be used at temperatures above 95°C in continuous pretreatment de-sizing (Choudhury 2014). In addition, modified amylases with improved performance, e.g. thermo-stable, could be developed by different protein-engineering methods, including random mutagenesis, homology considerations, site-directed mutagenesis, etc. Examples include α-amylases, which have been isolated from bacterial sources and subsequently characterized. These modified amylases, which have achieved higher heat stability, show activity over broader ranges of pH and show excellent potential in de-sizing (Diderichsen 1995; Shahid et al. 2016).

Higher de-sizing is achieved with thermo-stable enzymes, which improves the swelling of the fabric and subsequent absorption. The enzymes isolated from micro-organisms in extreme environments are naturally adapted to catalyse reactions under harsh conditions of temperature and pH, and can serve as better alternatives for industrial uses (Sharma and Satyanarayana 2013). Therefore, it is important that rational selection of micro-organisms from cold, moderate and extremely hot environments is adopted to produce desizing enzyme preparations with appropriate activities (Bertoldo and Antranikian 2002; Siddiqui 2015). Amylases from micro-organisms that thrive at relatively high temperatures have gained wider acceptance due to their shortened processing time on industrial scales. This has led to efficient industrial processes with improved absorbency over their mesophilic counterparts and conventional processes. De-sizing with low-temperature α-amylases (20–60 °C) takes more time than high-temperature amylases (95–100 °C or higher). In addition, de-sizing with high-temperature amylases can be performed in steam chambers to allow a fully continuous process (Shahid et al. 2016). Therefore, as raising the temperature for de-sizing facilitates efficient starch removal and reduces process duration, amylases from the high-temperature micro-organisms have gained wider acceptance (Saravanan et al. 2011).

Enzymatic de-sizing or biodesizing generates various types of simple sugars as end products. The sugars are nontoxic but influence the biological oxygen demand (BOD) of the wastewater in a negative manner. The de-sizing process consists of three main stages: impregnation, incubation and after-wash. Pre-wash is carried out to remove non-starch water-soluble additives from the fabric and facilitate the binding of amylase to the starch molecules. The starch is sequentially wetted and heated to gelatinize so that better contact between the enzyme and the substrate can be established. Impregnation takes place at temperatures above 70°C in a calcium-containing buffered solution. On the other hand, a longer incubation period at a lower temperature is required to soak the fabric with the enzyme solution at the optimum temperature.

The duration of the incubation period ranges from 2 to 16 hours and the variations of the incubation period are governed by several factors, including the stability and the activity of the enzyme relative to the processing temperature and the pH, size and nature of the fabric. During this period, wetting agents and nonionic surfactants could be employed to facilitate proper enzyme penetration and absorption, fibre swelling, and remove waxes, soils and synthetic sizing agents from the fabrics. Subsequently, the fabrics should be cleaned above 80°C in alkaline liquor and then washed off in neutral liquor. The sized yarns are then dried, followed by the occasional addition of beef or other fat in the size bath. This increases the smoothness of the sized yarn. Lipase enzymes are also added along with amylases into the de-sizing bath to remove fats. The addition of other enzymes into the process assists in efficient de-sizing due to the synergistic effects and removes natural impurities from the cellulosic materials (Choudhury 2014). The hydrophobic part of the size that arises from the addition of fat-based lubricants is efficiently removed by the lipases. These lubricants are difficult to eliminate even in scouring. Improved de-sizing has the advantages of shortening the processing time and thereby helps produce a higher quality end product in terms of the uniformity and the feel of the fabric against the skin (Madhu and Chakraborty 2017). Similarly, incorporation of peroxide or neutral cellulase with commercial amylase shows better wettability, higher dye uptake and lower stiffness (Ibrahim et al. 2004). Furthermore, glucoamylase in combination with α-amylase could be employed to carry out simultaneous de-sizing and acid demineralization in the case of cotton fabrics. This removes earth alkalis and cationic metal particles efficiently from cotton fabric and improves the de-sizing performance over normal washing or treatment in alkali.

3.2 Bio-scouring

The outer cuticle and primary walls of cellulosic fibres contain varying proportions of pectin, waxes, fats, proteinaceous materials, etc. These non-cellulosic impurities render improper dyeing and finishing of the cellulosic fibres because of poor wettability and dirty appearance. Primary cell non-cellulosic compounds remain inaccessible due to the presence of waxes in the thin outer wall (Hardin 2010; Madhu and Chakraborty 2017). It is necessary to remove the waxes for subsequent processing. These hydrophobic non-cellulosic components are usually eliminated by a hot aqueous alkaline scouring process so that the wettability of the fibre can be improved, which in turn ultimately facilitates uniform dyeing and finishing. However, the effectiveness of alkaline scouring in achieving satisfactory wettability is limited by the fact that it is resource-intensive and needs to be carried out at higher pH and temperature. The bio-scouring of cotton with enzymes has shown excellent promise as they tend to operate over a much broader range of pH and at lower temperatures (Hartzell and You-Lo 1998; Shahid et al. 2016). The requirement of less energy in bio-scouring in comparison with the conventional approach of scouring has rendered bio-scouring an eco-friendly approach. It is specific in targeting the non-cellulosic impurities and does not alter the substrate. As a result, cotton fibre can retain its inherent properties and the fabric remains softer to the touch after processing. Bio-scouring can also be used for blending cotton with silk, wool and cashmere as the severe alkaline conditions of classic scouring compromise the quality of these fibres (Csiszar et al. 2001; Sojka-Ledakowicz et al. 2006; Wang et al. 2007a; Madhu and Chakraborty 2017).

Followed by the removal of waxes from the outer wall, pectin remains the major non-cellulosic substance in cotton. It acts as the cementing or adhesive material between cellulosic and non-cellulosic substances. Therefore, the removal of pectin facilitates easy removal of the remaining non-cellulosic substances; hence, the process of bio-scouring is based on the concept of breakdown of pectin with the enzymes. The complex structure of pectin is broken down into simpler molecules by the enzymes broadly known as pectinases (Shahid et al. 2016; Madhu and Chakraborty 2017). Initially, bio-scouring was attempted with pectinases, proteases and lipases enzymes to remove the non-cellulosic impurities from the fibre. However, pectinases were found to be the most effective, followed by the lipases; the proteases were the least effective. This led scientists to characterize and optimize different pectinases for cotton fibre scouring.

The pectinases are usually effective in pH 5–9 and whether the pH of the bath should be kept alkaline or acidic depends on the type of pectinase. Both types show similar scouring effects; however, acidic pectinases work in low concentrations. Acidic medium could degrade the pectin within the pH range of 4–6 without pectinase, and helps in the removal of pectin in this condition. Bio-scouring was initially limited by the longer incubation period; however, the introduction of new pectinase types and incorporation of additives into the processes have led to sustainable industrial processing (Sahin and Gursoy 2005; Presa and Tavcer 2008; Ismal 2008; Madhu and Chakraborty 2017). The addition of non-ionic surfactants was proven to be efficient for enzyme penetration as they tend to lower the surface tension of fibres and aid the removal of wax and greasy material (Buchert et al. 2000; Traore and Buschle-Diller, 2000). In line with these efforts to work under higher temperature and alkaline conditions, a genetic modification technique was employed to produce a novel pectinase for bio-scouring with low dose requirements (Solbak et al. 2005). The synergistic effect of lipases in combination with pectinase was found to be effective as it increased the hydrophilicity of cellulosic textiles. Lipases were responsible for removing natural fats and lubricants to achieve better absorbency and enhance levelness in the processing of dyeing (Sangwatanaroj et al. 2003; Kalantzi et al. 2010; Madhu and Chakraborty 2017). Besides, cellulases were employed to hydrolyse cellulose chains for impurity removal (Ismal 2008;

Saravanan et al. 2008). Mixed enzyme systems incorporating pectinase in combination with lipases, proteases, cellulases, xylanases or cutinases were found to be very effective for this purpose (Li and Hardin 1997; Karapinar and Sariisik 2004; Wang et al. 2007b; Agrawal et al. 2008; Vigneswaran et al. 2013). Sometimes, single-step scouring and bleaching were carried out together to minimize the use of energy and water resources. For example, the alkaline pectinase was coupled with peroxide bleaching and the dyeing process for single-bath de-sizing, bio-scouring and bleaching of starch-sized cotton fabrics by a glucose-oxidase enzyme. The concurrent action of pectinase and peracetic acid was able to remove pectin and increase the degree of whiteness (Madhu and Chakraborty, 2017). Pectinases were also immobilized onto different platforms to achieve effective scouring over conventional alkaline processes or bio-scouring in aqueous media (Delcheva et al. 2007; Li et al. 2007). However, the availability of economically viable and commercial enzyme preparations either pectinases alone or in a mixture with other enzymes is below par for bio-scouring.

3.3 Bio-bleaching

Bleaching is considered to be one of the major steps of textile-wet processing prior to cotton dyeing. The natural pigments usually lead to a dirty appearance in the fibres after processing. The purpose of bleaching is to destroy or decolourize natural pigments present in the fibres to achieve a pure white appearance before dying. In the past, the fibres were treated with chlorine and oxidizing agents in extreme conditions to achieve whitening of fabrics. In recent times, hydrogen peroxide has been used more commonly at an industrial scale as a bleaching agent at alkaline pH and near boiling temperatures. The removal of residual hydrogen peroxide from fabrics requires a substantial amount of water, which constitutes a major problem in dyeing (Shahid et al. 2016).

Moreover, the radical reactions on the surface of the fabrics decrease the degree of polymerization and cause damage to fibres (Basto et al. 2007; Madhu and Chakraborty 2017). A number of alternative methods for bleaching have been explored in the textile plants, e.g. enzymatic bleaching with laccase/mediator systems, glucose-oxidases, peroxidases and peracids in situ generated enzymatically. However, the bio-bleaching process with laccase/mediator systems has been reported to be very effective due to its specific action on coloured substances (Pereira et al. 2005; Spicka and Tavcer, 2013a, 2013b). The use of laccases has demonstrated that the enzymes decolourize or eliminate coloured flavonoids in cotton bleaching (Hadzhiyska et al. 2006; Kim et al. 2007;) by alteration of phenolic hydroxyl groups (Pereira et al. 2005; Gonçalves et al. 2014).

A short-duration laccase-mediated system pre-treatment prior to hydrogen peroxide bleaching enhances the whiteness of cotton fabrics along with a lower dose requirement for hydrogen peroxide at a reduced temperature (Tzanov et al. 2003a, 2003b). The combined method of laccase-hydrogen peroxide cotton bleaching with ultrasound energy also enhances bleaching efficiency in mild conditions of pH 5.0 and 60°C for 30 min and remarkably improves product quality with the desired level of whiteness. Ultrasound energy has been reported to increase enzyme activity and improve the diffusion of the enzyme to the substrate surface (Abou-Okeil et al. 2010; Basto et al. 2007). Another enzyme, glucose oxidase (GOD), has shown great promise in cotton bleaching because of its specificity to produce hydrogen peroxide from glucose. This enzymatic system is quite unique in nature as it utilizes glucose in both desizing waste baths and scouring treatments, decreases water consumption and discharges less wastewater (Shahid et al. 2016). Reports show that combined one-bath desizing and bleaching or bleaching using reused de-sized bath produces better whiteness and improves mechanical properties like tensile and tear strength (Anis et al. 2009; Hebeish et al. 2013; Li and Hinks 2012). GOD produces hydrogen peroxide in slightly acidic to neutral conditions at low temperatures; however, bleaching requires high temperatures of 80–90°C and alkaline pH 11.0 to produce desirable effects (Anis et al. 2009; Farooq et al. 2013; Ramadan 2008). A bio-bleaching system employing arylesterases and hydrogen peroxide has also been reported (Auterinen 2011).

If newly developed enzymatic processes could be used globally, it could save approximately 10 trillion litres of freshwater and reduce greenhouse gas emission by 30 million metric tonnes annually (Shahid et al. 2016).

3.4 Bio-finishing

Bio-finishing/bio-polishing is the process of fibre surface modification and eliminates hair-like micro, fuzzy fibrils from the fabric surfaces or yarn by cellulases either before or after dyeing (Araujo et al. 2008; Saravanan et al. 2009, Choudhury 2014). Enzyme action on the fabric surface provides a softer finish and improved appearance. A ball of fuzz is called a pill and can present a major quality problem because pills result in an unattractive knotty fabric appearance. Therefore, the main advantage of bio-polishing is the prevention of pilling. Furthermore, the removal of fuzz improves colour brightness, hand feel and water absorbance of fibres, and provides a cleaner surface structure (Ibrahim et al. 2011). Traditional approaches use to emit gases from combustion. Enzymatic bio-polishing is considered an environment-friendly approach as it replaces gas singeing and no emission occurs (Choudhury 2014).

In the event of bio-polishing, cellulosic fibres are enzymatically hydrolysed by the combined actions of three-component enzyme systems comprising endoglucanases (EG) or endocellulases, exoglucanases or cellobiohydrolases (CBH) and cellobiases or β-glucosidases (Saravanan et al. 2009). In nature, cellulolytic systems exist in differential compositions in different cellulase preparations and work in a synergistic fashion. EGs cleave bonds along the length of cellulose chains in the middle of the amorphous region; CBHs work in the crystalline ends of cellulose chains and produce primarily cellobiose. Finally, β-glucosidases break cellobiose and soluble oligosaccharides into glucose (Madhu and Chakraborty 2017). The first reported commercially available cellulases for bio-polishing contain a combination of EGs, CBHs and cellobiases. They displayed the capacity to work on cellulosic fibres in a controlled and desired manner (Cavaco-Paulo 1998). A number of cellulosic fibre pre- and post-treatment methods are employed to enhance the efficiency of bio-polishing, such as soaking in water for a few hours and steaming prior to the enzymatic treatment (Pere et al. 2001). These methods improve the hydrolytic activity of cellulases on the fibres. In particular, steaming markedly enhances EGs' activity due to the swelling of less ordered sites on the fibre wall. Types of cellulases based on different types of cellulosic substrates, the optimization of process parameters and enzyme concentration are crucial to achieve effective bio-polishing. For example, acid cellulases-enriched EGs show effective bio-polishing of cellulosics (Bahtiyari and Duran 2010; Uddin 2010; Bai et al. 2012; Saravanan et al. 2013; Mojsov 2014).

The attachment of cellulases onto immobilization platforms offers the possibility of manipulating the action of the enzymes and its action on the fibre surface can be controlled. Various methods and immobilization matrices are used to attach cellulases to improve thermal stability and offer the potential to facilitate the reuse of the enzymes (Hirsh et al. 2010; Yin et al. 2013; Romo-Sanchez et al. 2014). Textile-specific application includes immobilization of acidic cellulases onto specific functionalized matrices, which improves the stability at neutral pH (Dincer and Telefoncu 2007), and commercial cellulases immobilized onto epoxy resins show better integrity of the enzyme than ion-exchange carriers after bio-polishing.

3.5 Bio-stoning or denim bio-wash

Denim garments are prepared from a warp face cotton fabric in which indigo dyes are used to dye warp yarn. To impart a worn look to them, the garments are subjected to wash treatment. During the process of stone-washing, the strong mechanical abrasive action of the pumice stones on fibre surfaces leads to non-homogeneous removal of dye from the fabric and reveals the white interior of the yarn, which causes the faded, worn and aged appearance (Cavaco-Paulo 1998; Bhat 2000; Choudhury 2014). However, denim washing with natural pumice stones suffers from some disadvantages. For example, the overload of pumice stones can cause severe physical damage to equipment and garments, and the stones give rise to particulate materials, which lead to the clogging of the machine drainage passage and sewer lines (Pazarlioglu et al. 2005; Yu et al. 2013).

Denim bio-washing has become one of the most successful and reliable enzyme-based systems in the textile industry owing to extensive research in recent times (Belghith et al. 2001; Yu et al. 2013, Cavaco-Paulo 1998). The application of enzymes in the form of microbial cellulases revolutionized denim washing by replacing stonewashing in the 1980s and nowadays more than 80 per cent of denim finishers use either cellulases or a combination of stones and cellulases to produce a worn appearance on denim (Araujo et al. 2008; Choudhury 2014). Cellulases remove indigo dye from the surface of the fibre in a non-homogeneous manner, a process known as 'bio-stoning' (Bhat 2000: 366.; Belghith et al. 2001: 257.). Cellulases have the ability to produce the same desired effect with gentler and much less mechanical means, reducing or even eliminating the use of stones. Therefore, enzymatic processes cause less damage to the garment and machines, increase productivity and generate less pumice dust in the laundry environment (Araujo et al. 2008; Choudhury 2014; Shahid et al. 2016).

For the purpose of denim finishing, a variety of cellulases with distinctive properties and actions are available. They are either used singly or in combination to achieve a specific desired appearance in the finishing process. They vary in their temperature requirements for optimal activity and range over 30°–60°C. They also differ in pH for their intended application and are classified as acid (pH 4.5–5.5), neutral (pH 6.6–7) or alkali (pH 9–10) cellulases (Bhat 2000; Araujo et al. 2008).

A major problem in denim finishing is the back-staining, re-deposition of released indigo in the process of stone-washing onto white portions of denim garments. Ideal biostoning would achieve high abrasion with low back staining. Back staining is attributed to the high-affinity interaction between indigo and cellulase enzyme and strong binding of cellulases to cotton celluloses (Madhu and Chakraborty 2017). Acid cellulases possess a higher affinity towards indigo than neutral ones. For this reason, neutral and endoglucanse rich cellulases are preferred to achieve better softening and indigo removal from denims (Araujo et al. 2008; Mojsov 2014). In addition, laccases are used as an eco-friendly alternative to the traditional chemical process. A number of solid laccase formulations are now commercially available for textile wet processing. Recently, the bio-desizing and bio-washing of denim garments were carried out in a one-step method with amylase, cellulase and laccase. The garments did not show any remarkable colour change when compared to the desized samples treated with cellulase and laccase. However, the treated fabrics with three enzymes showed lower back-staining with reasonable abrasion resistances up to 10,000 cycles. This was further improved by incorporating other enzymes such as lipase to improve the quality of desizing and for less colour reduction of denim garments. Furthermore, the use of chemical softeners could enhance some other characteristics of the garments, specially softness (Maryan and Montazer 2013).

4. Conclusion

Biotechnological progress has opened many windows for sustainable development (Petruzzelli et al. 2015; Coccia 2017). Biotechnology has a strong relationship with sustainability in textile manufacturing with the incorporation of industrial-scale enzymes and their related processes. We can view sustainable textile development as processes where the needs of the present manufacturing are met without reducing the opportunity for future incorporation of greener production systems. In this respect, sustainable development encompasses both harmony and synergy in the utilization of resources, the process of investment and technological development. The ultimate objective is to increase the opportunity to meet both current and future needs in an efficient and responsible manner (Broman and Robèrt 2017). In addition, industrial sustainability takes into account sustainable manufacturing and processing with the objective of ensuring environmental and social sustainability (Turker and Altuntas 2014) . However, an industry is deemed sustainable when it can assure that the present demands are met without harming the potential for meeting future generations' needs.

Environmental and market implications

Biotechnology can ensure greener processes in the textile industry because biotechnology-powered manufacturing and processing systems, essentially enzymatic textile processing, use less materials and energy. It guarantees reduced greenhouse gas emission, less dependence on nonrenewable resources and increased use of renewable resources (Gavrilescu 2010). Biotechnology-fuelled sustainable products, such as textile enzymes, are better performing, more profitable, durable, less toxic, easily recyclable and biodegradable in the environment (Bolis et al. 2017). In the current competitive and challenging business environment, enzymatic biotechnology is promising in terms of enhancing sustainability concepts in the textile manufacturing supply chain. This enables organizations to achieve a 'competitive position' in the world market by replacing chemical-based processing (Ansari and Kant 2017). By focusing on biotechnology, organizations have adopted sustainable supply chain management (SSCM). SSCM is an integration of three facets of sustainable development: economic contribution, social performance and environmental performance (Khodakarami et al. 2015). The scope for the application of biotechnology to textile industrial processes results in opportunities for assessing frameworks for addressing economic, societal and environmental challenges, including sustainable development, cost minimization and business competitiveness (Ribeiro and Shapira 2018).

Biotechnology has used enzymes as an alternative to the harmful chemicals in the textile industry. Enzymes are found in naturally occurring micro-organisms, such as bacteria, fungi and yeast. Enzymes are protein molecules that act as catalysts and are found in micro-organisms, such as bacteria, fungi and yeast. Use of enzyme has created scope for biotechnology to reduce costs in the manufacturing process, with reduced consumption of water, electricity and fuels, and improvement in the final product. This contributes to business competitiveness. Apart from the cleaning process, textile enzyme is being used in the treatment of cotton fibres. Enzymes enable a faster and softer treatment process, which results in less chemical and energy consumption (OECD 2011).

Limitations and further research

This article has some limitations linked to the fact that it is literature based. In addition, despite our effort to simplify the complex scientific data examined, there remain lots of key terminologies that may not be accessible to a number of stakeholders in the developing world. Consequently, we suggest that future research consider a glossary of terms to facilitate reading by stakeholders who are unfamiliar with some key scientific and technological terms. We also see the need for future research to be more empirical in nature and evaluate the extent of the implementation of biotechnologies in textile processing in developing countries and emerging issues, which will enable science to take corrective actions or seek improvements in such technologies.

Acknowledgement

The work is funded by the Commonwealth Rutherford fellowship.

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Table 1: Application of enzymes in textile processing and their mechanism of actions.

Major group of enzyme	Name of specific enzymes	Application in textile processing	Mechanism of actions
Hydrolases	Amylase	Bio-desizing	Breakdown of starch into simpler sugars
	Lipases	Bio-desizing; Detergent formulation	Decomposition of fats and oils into glycerol and fatty acids Removal of lipid stains
	Cellulases	Bio-scouring; Bio-stoning, Bio-finishing, Wool carbonization	Breakdown of cellulose into soluble products
	Pectinases	Bio-scouring	Decomposition of pectin
	Cutinases	Bio-scouring	Hydrolysis of insoluble cutin into cutin monomers
	Xylanases	Bio-bleaching	Degradation of the linear polysaccharide beta-1,4-xylan into xylose
	Proteases	Wool modification	Hydrolysis of peptide bonds of proteins into soluble polypeptides and amino acids

Oxidoreductases	Laccases	Bio-bleaching; Dyeing, Textile effluent decolourization.	Degradation of recalcitrant organic compounds through catalysing transfer of electrons from one molecule
	Catalases	Peroxide removal	In situ decomposition of peroxide

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