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ENZYMATIC VALORIZATION OF XYLAN: MICROBIAL XYLANASES AND THEIR INDUSTRIAL IMPLICATIONS

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ABSTRACT
The primary component of plant hemicellulose, xylan, has β-1,4-xylosidic bonds that are hydrolyzed by a class of hemicellulolytic enzymes called xylanases. Numerous microbes, such as bacteria, fungus, and actinomycetes, as well as non-microbial sources including mollusks and plants, produce these enzymes. Xylanases have great potential for a variety of commercial uses due to their capacity to degrade intricate xylan structures into simpler xylose sugars. A thorough examination of xylanase enzymes is provided in this review, with special attention to the biological distribution and structural complexity of its main substrate, xylan. It also looks into the enzymatic systems that break down xylan, including as β-xylosidases, endoxylanases, and auxiliary enzymes like esterases and arabinofuranosidases. The microbiological sources of xylanase are specifically examined, and bacterial and fungal strains are compared according to their activity profiles, ideal conditions, and suitability for industrial uses. Additionally, the review outlines the biotechnological significance of xylanases in industries such management of waste, textiles, animal feed, food processing, pulp and paper, and biofuel generation. With this synthesis, we highlight the enormous industrial potential of xylanases and promote more investigation into how to best optimize, immobilize, and incorporate them into environmentally friendly manufacturing methods.

KEYWORDS: Xylan, enzymatic hydrolysis, food processing, biofuel, waste management.

1. INTRODUCTION

The 1,4-β-d-xylosidic bonds in xylan have been endohydrolyzed by xylanases, which are glycosidases (Collins et al., 2005). These ubiquitous enzymes, that have been made by species' wide range, like algae, bacteria, fungi, gastropods, protozoa, along with anthropods, participate in plant cell infection by plant pathogens along with xylose synthesis, a major carbon source for cell metabolism (Prada and R.A., 1995). One of significant industrial polysaccharide utilization, 2ndmost prevalent natural polysaccharide, has been enzymatic hydrolysis of this xylan (Beg et al., 2001; Polizeli et al., 2005). In plants, xylans(also called hemicelluloses), are located beneath cellulose fibers and between lignin and they are hydrogen-bonded to cellulose and interspersed with it at different locations (Beg et al., 2001).

Xylanases are an enzyme group in charge of the linear polysaccharide's full hydrolysis β-1,4-xylan, reducing it to simpler compounds, mostly xylose, and thus having vital function in hemicellulose degradation (Burlacu et al., 2016). These enzymes are glycoside hydrolases

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generated by diverse organisms like fungi, bacteria, actinomycetes, as well as even marine algae, plants, and invertebrates (Singh et al., 2023). Among these, microbial sources—particularly filamentous fungi like *Aspergillus* as well as *Trichoderma*, moreover bacteria including *Bacillus* as well as *Streptomyces*—have been of particular industrial interest due to their high enzyme yields and adaptability to fermentation conditions (Sunna & Antranikian, 1997; Mandal, 2015). Marine-derived microbes have gathered attention in recent years for producing xylanases that remain active under tough conditions, such as high salinity and temperature, which are advantageous for applications in textile, detergent, along with biofuel industries (Singh et al., 2023). Xylanases, along with microbes that generate them, have now been employed in waste management processes, where they break down xylan into renewable fuels and chemicals. Additionally, these enzymes have been employed in industries including food processing, agro-fibre production, moreover paper and pulp sectors, here they contribute to minimizing environmental influence (Collins T. et al., 2002). In industrial contexts, xylanases have already been applied widely. In pulp as well as paper sector, they aid in biobleaching by facilitating xylan-lignin complex removal, thereby reducing environmentally damaging chlorine-based chemicals utilization(Viikari et al., 1986; Beg et al., 2001). For food technology, xylanases enhance dough handling, improve bread quality, and clarify juices (Subramaniyan & Prema, 2002; Mandal, 2015). In animal nutrition, they improve digestibility by breaking down arabinoxylans, while in biofuel production, they contribute to the enzymatic saccharification of lignocellulosic materials, increasing sugar yield and fermentation efficiency (Lee, 1997; Dominguez, 1998; Singh et al., 2023). This review seeks to offer thorough xylanase summary, focusing on structural complexity of its primary substrate, xylan, and the natural distribution of the enzyme across various plant sources. We also look at the enzymatic processes that break down xylan, the natural and synthetic microbial sources of xylanase, and the important roles that the enzyme plays in biotechnological processes range, including energy production, food processing, environmental sustainability, and the pulp and paper industry. Through this synthesis, we hope to highlight the enzyme's industrial potential and encourage more investigation into its unique applications and optimization.

2. XYLAN, THE SUBSTRATE FOR XYLANASES

Xylan, has been the substrate on which the enzyme xylanases act. It has been 2ndmost prevalent polysaccharide in nature and that makes up major structural component in plant cells. It comprises almost 1/3rd of the planet's recoverable organic carbon (Prade et al., 1995).

Xylan has been primary hemicellulose constituent, complex group of polysaccharides which also includes several other important heteropolymers. These include glucomannan, which consists of D-mannose as well as D-glucose, galactoglucomannan, D-galactose combination, D-glucose, and D-mannose, arabinogalactan, made up of D-galactose and arabinose, and xyloglucan, a polysaccharide composed of D-glucose and D-xylose (Shallom and Shoham, 2003). These diverse components of hemicellulose play crucial roles in the structure as well as plant cell wall properties, contributing to rigidity, flexibility, and interaction with other biopolymers such as cellulose.

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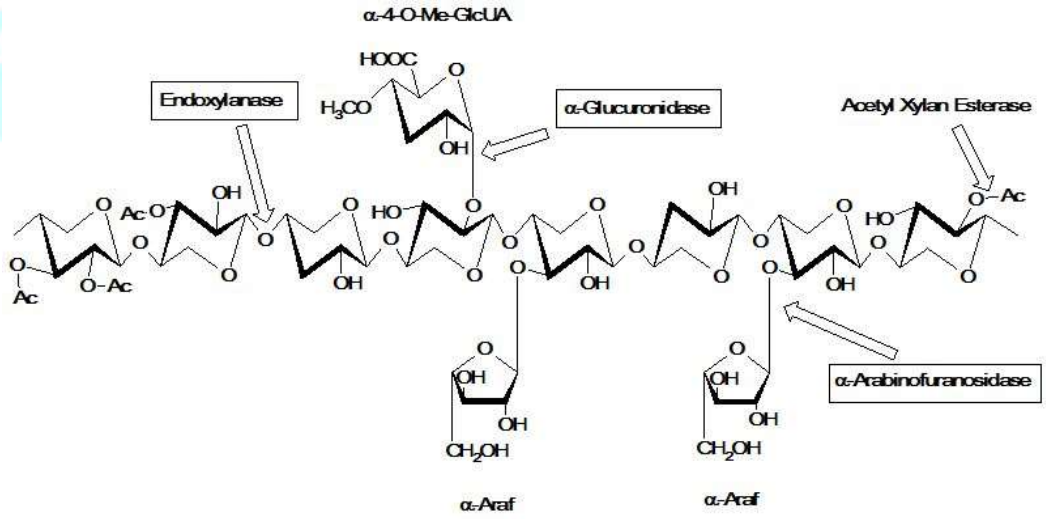
Primary polymeric secondary plant cell walls components have been xylan, cellulose (1,4-b-glucan), as well as lignin, complex polyphenolic molecule (Kulkarni et al., 1999). All three cell wall structures interact with components through non-covalent along with covalent bonds; xylan is located at lignin-cellulose interface and is thought as crucial for fiber cohesion as well as plant cell wall integrity (Beg et al., 2001).

3. STRUCTURE AND DISTRIBUTION OF XYLANS

Four primary kinds of xylans can be distinguished based on the makeup of their substituents (Motta et al., 2013): First type is Arabinoxylans, that are made up of only the side chains that have single terminal units of α-Larabinofuranosyl; second type of xylan is Glucuronoxylans that are made up of only "α-Dglucuronic acid along with 4-O-methyl ether derivative; third type is Glucuronoarabinoxylans, that contain both α-Dglucuronic (4-O-methyl-α-D-glucuronic) acid along with α-L-arabinose and fourth is Galactoglucuronoarabinoxylans", that have been made up of xylans' complicated oligosaccharide side chains that have terminal β-Dgalactopyranosyl residues (Motta et al., 2013).

Furthermore, there is a different class of xylans called homoxylans that are made entirely of xylosyl residues. These xylan types are mostly unavailable in nature. They can only be isolated



from few sources such as the guar seed husks and stalks of tobacco (Sunna and Antranikian, 1997).

These groupings become more complex as the xylans become more replaced and less linear. This happens because the side chains of the xylan molecule affect its physical conformation, solubility, along with other hemicellulosic components' interaction, they are having an influence over the manner as well as enzymatic cleavage degree (Kulkarni et al., 1999).

Fig1. Xylan structure along with xylanolytic enzymes. (Antranikian and Sunna, 1997)

Xylan has been found in numerous plant species where it has been broadly dispersed in various plant cells and tissues (Kulkarni et al., 1999). It contributes significantly to the plant cell walls'

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structural integrity, with particularly high concentrations in hardwoods from angiosperms, there it accounts for15–30%total cell wall composition. Softwoods from gymnosperms contain slightly lower amounts, approximately 7–10% xylan, while annual plants typically have less than 30% xylan in their cell walls (Singh et al., 2003). Xylans found in grasses moreover other annual plants are primarily arabinoxylans composed, whereas, in hardwoods, xylan is found mainly as "O-acetyl-4-O-methylglucuronoxylan. In contrast, xylan in softwoods exists predominantly as arabino-4-O-methylglucuronoxylan (Kulkarni et al., 1999). Additionally, certain plant species, including esparto grass (Chanda et al., 1950), tobacco (Eda et al., 1976), along with some coastal algae (Bary and Dillon, 1940; Nunn et al., 1973"), contain linear forms of unsubstituted xylan. These plants feature xylopyranosyl units that are connected through both 1,3-β and 1,4-β-glycosidic bonds, contributing to the unique structural properties of xylan in these species (Nunn et al., 1973; Percival and Chanda, 1950).

4. XYLAN HYDROLYSIS BY ENZYMES

Over a hundred years ago, Hopper-Seyler was among the first to observe enzymes' role to break down xylan (Bastawde, 1992). Because of its complex and heterogeneous structure, the full breakdown of xylan necessitates coordinated multiple hydrolytic enzyme action, each with distinct specifications of substrates as well as action mechanisms.

Xylanolytic enzyme structure members include β-xylosidase, "β-1,4-endoxylanase, α-glucuronidase, acetyl xylan esterase, α-L-arabinofuranosidase, as well as phenolic acid esterase (Beg et al., 2001; Dhiman et al., 2008; Motta et al., 2013"). All such enzymes function in together ultimately achieving xylan- the substrate breakdown into its component sugars. β-xylosidases along with Endoxylanases have been key enzymes accountable for breaking down xylan into its monomeric pentose sugars. The internal glycosidic linkages within the xylan backbone are cleaved as a function of endoxylanases, resulting in the release of short-chain xylooligosaccharides. In contrast, β-xylosidases act on these oligosaccharides by sequentially removing xylose units from their non-reducing ends (Motta et al., 2013).

Enzymes like "ferulic esterase, acetyl esterase, glucuronidase", along with arabinosidase catalyse various side chains breakdown adhered to backbone of xylan substrate (Dhiman et al., 2008). Studies have indicated that microorganisms, particularly bacteria like *Bacillus* & *Streptomyces* species, as well as fungi like *Aspergillus* &*Trichoderma*, have been primary endo-1,4-β-xylanases manufacturers.

Exo-"β-1,4-D-xylosidase facilitates β-1,4-D-xylo-oligosaccharides breakdown by cleaving off D-xylose units from their non"-decreasing ends, one at a time. While endoxylanases help in the degradation of xylan by releasing xylose, they do not affect β-xylosidase capability to hydrolyze xylobiose. Various studies have highlighted fungi and *Bacillus* species as major sources of these enzymes (Subramaniyan and Prema, 2002). Additionally, α-L-arabinofuranosidases have vital function in breaking down non-decreasing terminal α-L-arabinofuranosyl residues of arabinoxylans, arabinans, along with arabinogalactans. Such

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enzymes have primarily been produced by actinomycetes, fungi, and certain bacterial strains, such as *Bacillus polymyxa* and *Rhodothermus marinus* (Burlacu et al., 2016).

α-D-glucuronidases catalyze "α-1,2-glycosidic linkages hydrolysis that binds xylose to its 4-O-methyl ether linkage or D-glucuronic acid. Esterases are necessary for the full hydrolysis of natural glucuronoxylans in order to liberate the bound phenolic and acetic acids. Xylose-acetic acid linkages are broken by acetyl xylan esterase. Whereas, arabinose side chain residues are broken by feruloyl esterase" to ferulic acid, as well as by p-coumaroyl esterase to pcoumaric acid (Burlacu et al., 2016).

Xylanases are typically inducible enzymes that have been produced in response to either pure xylan/xylan-rich residue presence in the environment (Balakrishnan et al., 1997). For practical applications, it is necessary to immobilize xylanases. Thus, the microbe or the xylanase enzyme needs to be immobilised on a solid medium. This method has multiple benefits, including increased enzyme stability, ease of product separation, and repeated use of the enzyme (Beg et al., 2001).

5. VARIOUS MICROBIAL SOURCES FOR OBTAINING XYLANASE

Numerous researchers have reported the presence of enzyme xylanase across biological source varieties, like fungi, yeasts, bacteria, marine algae (Mandal, 2015), as well as plant seeds, crustaceans, and mollusks such as snails (Polizeli et al., 2005). Despite this wide biological distribution, microorganisms—particularly fungi and bacteria—remain the most commonly exploited and commercially viable sources for xylanase production. These microbial xylanases possess distinct biochemical and functional characteristics that contribute to their effectiveness for wide industrial as well as biotechnological array applications. Their specific properties, such as stability under various pH and temperature conditions, make them highly suitable for use in sectors ranging from biofuel production and food processing to paper and textile manufacturing.

5.1 Bacterial Xylanases

Xylanases typically show peak catalytic action inside temperature range 35-60°C, that makes it suitable for different industrial processes that operate under moderate thermal conditions. Notably, xylanases derived from bacterial sources and Actinomycetes—particularly strains belonging to *Bacillus*, *Pseudomonas*, and *Streptomyces* genera—demonstrate robust enzymatic performance across a relatively broad pH spectrum, of range 5-9 pH. This wide pH tolerance enhances their versatility for application in environments with fluctuating or extreme pH levels (Mandal, 2015; "Beg et al., 2001; Motta et al., 2013).Table 1 lists bacterial strains whose xylanase activity was investigated (Dhiman et. al, 2008; Mandal, 2015; Maheshwari and Chandra, 2000"; Amore et al., 2014).

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Table 1. Bacteria that produce Xylanase

Bacterial Species	**Type of Xylanase Produced**	**Reference**
Bacillus subtilis	Thermostable, alkaline	Chakdar et al. 2016
Bacillus pumilus	Alkaline	Chakdar et al. 2016
Bacillus halodurans	Alkaline	Chakdar et al. 2016
Stenotrophomonas maltophilia	Thermostable	Chakdar et al. 2016
Paenibacillus macerans	Acidophilic	Chakdar et al. 2016
Actinomadura sp.	Alkaline	Chakdar et al. 2016
Flavobacterium frigidarium	Cold-adapted	Chakdar et al. 2016
Clostridium thermocellum	Thermostable	Chakdar et al. 2016
Thermotoga sp.	Thermostable	Chakdar et al. 2016
Geobacillus thermoleovorans	Alkaline	Chakdar et al. 2016
Streptomyces cyaneus	Xylanase	Ninawe et al., 2006
Streptomyces tendae	Xylanase	Ninawe et al., 2006
Streptomyces caelestis	Xylanase	Ninawe et al., 2006

Research on *Bacillus* species revealed that higher temperatures and alkaline pH increased xylanase activity. Consequently, because of their thermostability and alkali tolerance, bacterial xylanases are employed in industrial applications (Mandal, 2015).

5.2 Fungal Xylanases

Xylanase has been generated in significant quantities by fungi ("Aspergillus species, Fusarium species, and Penicillium species), which also release enzymes extracellularly (Nair and Shashidhar, 2008). Furthermore, fungal xylanases show more activity than yeast"/bacteria. Fungal-derived xylanases, however, have certain properties that prevent them from being used in some industrial applications. The majority of these xylanases function best at pH values between 4-6 and temperatures below 50ºC (Beg et al., 2000). For example, paper &pulp industry needs temperatures above 60ºC and an alkaline pH therefore fungal xylanases cannot be utilized there (Mandal, 2015). There aren't much research describing fungal xylanases without cellulase activity, which is another issue with fungal xylanases (Subramaniyan and Prema, 2002).

Table 2 lists the fungal strains which were examined for determining their xylanase activity ("Mandal, 2015; Huitron et al., 2008; Ja'afaru, 2013; Taneja et al., 2002; Haltrich et al., 1993; Ghanen et.al, 2000; Haltrich et al., 1996").

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Table 2. Fungi that produce Xylanase

Fungal Species	Type of Xylanase Produced	Reference
Aspergillus niger	Thermostable xylanase	Bakri et al., 2020
Aspergillus tubingensis	Single xylanase (Xyn60; 36 kDa)	Rastogi et al,. 2022
Aspergillus fumigatus	Endo-1,4-β-D-xylanohydrolase; thermostable	Saroj et al., 2018
Aspergillus terreus	High xylanase activity at pH 7, optimal at 474 U/mL	Bakri et al., 2020
Trichoderma harzianum	Xylanase with maximum 2137.75IU/gds activity using mycological peptone	Guan et al., 2016
Cladosporium oxysporum	Alkaline xylanase; optimal activity at pH 8.0, 55.92U/mL having NH_4Cl as nitrogen source	Guan et al., 2016
Neurospora intermedia	Xylanase with Vmax of 14.77 U/mL; produced effectively in wheat-based biorefinery setups	Shahryari et al., 2019
Alternaria alternata	Extracellular xylanase; significant activity observed in soil isolates	Al-Qahtani et al., 2022
Penicillium chrysogenum	Xylanase producer; moderate occurrence in soil samples	Al-Qahtani et al., 2022
Rhizopus microsporus	Xylanase producer; moderate occurrence in soil samples	Al-Qahtani et al., 2022

Both “solid state fermentation (SSF) and submerged fermentation (SmF)” can create xylanases, with SSF having significantly greater enzyme productivity than “SmF (Nair and Shashidhar, 2008). However, the production of fungal” xylanases on a big scale poses various challenges such as a very slow generation time the co-production of oxygen-transmission-reducing polymer of high viscosity (Mandal, 2015).

6. APPLICATIONS OF MICROBIAL XYLANASES

Over previous few years, a notable surge has been there in demand for xylanases (Dhiman et al., 2008). These enzymes, primarily produced by microorganisms, have gained considerable interest because of their diverse utilizations in industrial sectors like paper and pulp processing, food manufacturing, as well as animal nutrition. Their ability to contribute to the cost-effective synthesis of a wide array of valuable compounds further highlights their industrial significance. Among the various end-products are single-cell proteins, different enzymes, biofuels (in both liquid and gaseous states), solvents, and syrups based on sugar, which are directly utilized or serve as feedstock for subsequent microbial processes (Kuhad and Singh, 1993). Because of

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these versatile applications, xylanases are now recognized as some of the most commercially valuable enzymes in biotechnology (Dhiman et al., 2008).

6.1 Pulp and paper industry

Chemical bleaching has been utilized to make paper brighter in this industry. This lowers the pulp's yield and viscosity and seriously destroys the cellulose components. Reducing viscosity is undesirable since it is correlated with the strength of the paper and cellulose polymerization degree (Cheng et al., 2013).

Few studies examined how xylanase affects pulp yield and viscosity; instead, the researchers concentrated on employing the enzyme primarily to reduce chemical usage "(Cheng et al., 2013). This technique" frequently entails applying xylanase treatment to the pulp before bleaching using chemicals ("Martin-Sampedro et al., 2012"). Presence of Xylanase hydrolyzes "the reprecipitated xylan", facilitates pulp bleaching and lowering the need for chemicals. Via this technique the quantity of dangerous materials discharged into the environment is reduced (Cheng et al., 2013).

6.2 Food industry

By increasing certain "bread volume, xylanases enhance the bread's quality. When" amylase and xylanase are combined, this is further improved ("Maat et al., 1992"). Xylanases have also been utilized in baking rye, where the dough becomes slack and mushy due to the presence of this enzyme (Subramaniyan and Prema, 2002). Crumb production is delayed to allow the dough to expand while the baking of the bread is ongoing (Mandal, 2015).

Xylanases have also been utilized as dough strengtheners because they give the dough exceptional tolerance to changes in flour quality and processing factors (Subramaniyan and Prema, 2002). Furthermore, bread with a higher content of arabinoxylo-oligosaccharides would be healthier (Mandal, 2015). When baking biscuits, xylanase has been advised for lightening cream crackers as well as enhancing their flavour and texture (Mandal, 2015). Xylanase can be utilized in conjunction with cellulase and pectinase to generate dextrans, which is used as a food thickener (Mandal, 2015).

6.3 Animal feed

Broiler hens' weight gain as well as feed conversion efficacy are enhanced when xylanases are added to their rye-based diet because they decrease intestinal viscosity (Bedford and Classen, 1992). In addition to improving grain feed as well as agricultural silage's nutritional value when used as a pretreatment for forage crops, xylanases also increase ruminant feeds' digestibility along with facilitating composting ("Subramaniyan and Prema, 2002; Kuhad and Singh, 1993; Bedford and Classen, 1992"). Xylan removal completely from dietary components is undesirable as this type of hemicelluloses are essential for the body, the absence of which may lead to gastrointestinal issues (Mandal, 2015).

6.4 Biofuel

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As energy supplies become more scarce, the biofuels' production has been turning increasingly crucial. Xylan activity in collaboration with various enzymes, like ligninase, mannanase, xylosidase, glucosidase, glucanase, etc., lignocellulosic biomass could be used in biofuels production(xylitol and ethanol) (Dominguez, 1998). Lignocellulose delignification produces components hemicellulose along with cellulose which is 1st step for bioethanol manufacture. In next few steps, carbohydrate polymers are broken down into simple sugars, followed by the fermentation of a mixture of hexose as well as pentose for producing bioethanol (Lee,1997)

6.5 Fabric bio-processing

Without compromising the fiber's strength during spinning, xylanase treatment can greatly reduce hemicellulosic contaminants, improving the fiber's capacity to absorb water. After desizing, the fiber eventually gets smoother and softer (Dhiman et al., 2008). Xylanase-based bio-processing has risen to popularity in the textile industries given its eco-friendly and fiber-preserving capabilities. These enzymes specifically hydrolyze hemicellulosic xylan without affecting the cellulose backbone, thereby retaining the tensile strength of fibers during mechanical processing. Their application effectively reduces hemicellulose content, which enhances the wettability, softness, and smoothness of natural fibers such as cotton, flax, and jute after desizing. Unlike conventional chemical methods that can damage fibers and pollute wastewater, xylanase treatment offers a sustainable alternative with lower environmental impact. This enzymatic approach not only improves dyeability and fabric finish but also facilitates better fiber separation during retting, especially in bast fibers like hemp and kenaf (Garg et al., 2016; Bajaj et al., 2021). Recent advancements in microbial xylanase production and enzyme engineering have further increased the efficiency and specificity of these biocatalysts, making them more viable for industrial-scale textile applications (Chadha et al., 2019; Raj et al., 2020).

6.6 Beverages and Juices Industry

Xylanase, together with cellulase as well as pectinase, helps in juice clarification, liquefication of vegetables as well as "fruits (Beg et al., 2001), pulp stabilization, lowering viscosity, and hydrolysis of substances which could make concentration of juices cloudy and thus difficult for the juices to be cleared physically or chemically (Polizeli et al., 2005; Mandal, 2015). In particular, α-L-arabinofuranosidase along with β-Dglucopyranosidase have been utilized to aromatize wines, musts, as well as fruit juices (Spagna et al., 1998). Moreover, xylanolytic enzymes" have been utilized to extract plant oils, coffee, along with starches (Subramaniyan and Prema, 2002). Xylanases, which are utilized as arabinoxylans pre-treatment comprising substrates (barley, wheat), reducing viscosity and enhancing procedure efficacy in beer fermentation industries (Subramaniyan and Prema, 2002).

6.7 Treatment of plant cells

Acylated sterol glycoside levels rose and phytoalexin synthesis was stimulated when "tobacco suspension cells were treated with a purified endoxylanase from Trichoderma viride" (Moreau

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et al., 1994). Additionally, it has been demonstrated that transgenic tobacco plants rhizosecrete a truncated "Clostridium thermocellum bacterial xylanase gene (Borisjuk et al., 1999"). According to Beg et al. (2001), several xylanases improve cell wall maceration for plant protoplasts production.

6.8 Hemicellulosic waste

Xylan, hemicellulose's principal component, is abundantly present in various lignocellulosic and hemicellulosic waste streams. These wastes, generated in large volumes from agricultural residues, forestry by-products, and municipal solid waste, represent a significant environmental burden if not properly managed. The growing accumulation of such organic waste highlights the need for sustainable and efficient treatment methods. In this context, enzymatic hydrolysis using xylan-degrading enzymes offers a promising approach for the bioconversion of xylan-rich materials into value-added products, thereby contributing to both waste reduction and resource recovery (Subramaniyan & Prema, 2002; Rani & Nand, 1996).

6.9 Surfactants

Alkyl glycosides, a class of surfactants derived from simple sugars, are widely used across various industrial applications due to their effective surface-active properties. However, the conventional production of these compounds from monomeric sugars involves several complex and costly processing steps. Utilizing polysaccharides as a starting material has been suggested as a more practical alternative, as it simplifies the overall manufacturing process by reducing the number of required steps (Matsumura et al., 1999). In this regard, xylanase presents both a challenge and an opportunity, as it can facilitate the breakdown of xylan-rich polysaccharides into usable sugars for alkyl glycoside production. Additionally, xylanase has found valuable applications in the detergent industry. When incorporated into detergent formulations, it improves their effectiveness in removing stains originating from organic sources such as fruits, vegetables, soil, and grass, thereby enhancing overall cleaning performance (Kumar et al., 2004; Dhiman et al., 2008).

6.10 Retting of flax fibres

The debarking process, the initial stage of wood processing, uses a combined xylanase-pectinase system. When xylanases are added, it leads to the improvement of the retting process. More uses for this collaborative system include the liberation of fiber from plants in place of retting and bast fibers degumming including hemp, flax, jute, as well as ramie (Beg et al., 2001).

7. CONCLUSION

Xylanases have emerged as indispensable biocatalysts with extensive implications across environmental, industrial, and biotechnological domains. They are at the centre of many sustainable developments, from pulp biobleaching and biofuel generation to animal nutrition and food enhancement, because of their effectiveness in breaking down xylan, a structurally

varied and plentiful plant polysaccharide. Numerous xylanase-producing microorganisms are available for application-specific enzyme selection and engineering, especially thermotolerant and alkaliphilic bacterial strains. Optimizing enzyme stability, activity under harsh circumstances, and large-scale production—especially for fungal xylanases—remains a difficulty despite significant advancements. The effectiveness and economy of xylanase applications could be greatly increased by further research into genetic engineering, immobilization methods, and synergistic enzyme systems. Xylanases stand out as important contributors to a bio-based, circular economy as companies progressively shift toward eco-friendly methods, deserving of further research into their full biotechnological potential.

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