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Review Article

Xylanase-Producing Microbes and Their Real-World Application

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The present study is focused on the availability of microbial sources capable of producing xylanase, a hemicelluloses-degrading enzyme with multiple modes of action along with specificity, and their real-world applications. For the accumulation of suitable data, article surfing was carried out using multiple search engines viz. Hinari and PubMed; irrelevant and duplicate articles were discarded and articles were summarized in a narrative way herein. This review article was written aiming to bridge the recent research activities with the commercial activities of xylanase going on around the globe. The readers would be able to acknowledge themselves with the basic idea of the hydrolytic enzyme xylanase, their classification representing their different families, presenting the affinity of different families at the structural level, the sources, and the commercial implications that have been going on alone and in combination. The major hemicellulose, Xylan is digested with the help of combination other enzymes such as alpha-amylase, subtilisin, protease, and endo-1,3(4)-β-glucanase along with xylanase. Xylanase has a diverse applications such as pharmaceutical, food and feed, bakery, paper and pulp, textile, and bio-refinery industries. The objective of this review article is to compile microbial sources of this enzyme and its application for betterment of human kind.

1. Introduction

Xylan is one of the most plentiful polysaccharides on Earth [1]. Xylan is the major hemicellulosic constituent found in soft and hard wood and is the next most abundant renewable polysaccharide after cellulose. Xylanases are hydrolytic enzymes that catalyze the cleavage of the β-1,4 backbone of xylan [2] randomly which results in the production of diverse products which include xylobiose, xylotriose, xylotetraose, and longer and/or branched xylo-oligomers (XOS) [3, 4].

Scientifically, xylanase is known as endo-1,4-β-xylanase (EC 3.2.1.8). Xylanases (endo-1,4-β-xylanases; EC 3.2.1.8) catalyze the hydrolysis of β-1,4-xylosidic bonds of xylan, constituting a class of enzymes that are critical for the degradation of hemicellulosic polysaccharides in biomass [5]. Due to the complex nature and diversity of xylan, enzymatic degradation must be carried out by multiple hydrolytic enzymes with multiple modes of action and specificities [6]. Xylanase is preferred due to its involvement in cleaving glycosidic bonds and endo-xylanase [7].

Bacteria, fungi, actinomycetes, and yeasts which include cellulomonas, bacillus, micrococcus, aspergillus, penicillium, streptomyces, chytridiomycetes, trichoderma, and ruminococcus have also been reported for xylanase production [6–8].

Abundant use of bacteria for enzyme production is because they are capable of growing rapidly, are capable of genetic modification easily, and have ease of growth and regulation of production [9], though fungi are considered as the most potent xylanase producers [6]. Industrial processes are carried out at a higher temperature and extreme pH which is a supporting fact for the suitability of thermostable xylanases obtained from the thermophilic microorganisms and those obtained from their mesophilic counterparts [10]. This is the main reason for the increasing demand for the isolation and screening of thermophilic microorganisms for the production of novel thermostable xylanases for industrial applications, and it is preferred to adapt genomic strategies and various molecular approaches conducted via bioinformatics tool. Hence, produced xylanase has been reported to have stable, higher enzyme activity [6].

The xylan processing arena makes the use of xylanase as it is eco-friendly and can reduce the processing cost. The enzymatic action of xylanase in the paper industry can improve the efficiency of bleaching agents (hydrogen peroxide, ozone, and chlorine) in a bakery; it can aid in the improvement of the bread texture; and in the juice and wine industry, it can aid in the clarification steps and hence improve the quality. Along with these applications, xylanase has been reported in animal feed additive formulations as well. Besides all these beneficial applications, few limitations hindering its commercialization are present. The complex and diverse nature of xylan, the cost of the enzyme along with thermal instability, and the pH-dependent nature of xylanase are limiting factors hindering further commercialization [11]. With the aid of various engineering procedures, limiting factors hindering commercialization are diminished, increasing its demand in the diverse industrial arena that includes the paper and pulp industry, pharmaceuticals, and food and feed. [10].

The synergistic action of xylanase has been observed when used in combination with pectinase, cellulase, phytase, glucanases, glucose oxidase, α-amylase, and malting amylase. A combination of xylanase along with pectinases and cellulases has been reported for yield increment when used for clarification and extraction of vegetable and fruit juices. The similar, combinational benefits of xylanase, when used in combination with cellulase and phytase, have been reported for showing improvements in the performance and feed value of animals. A combination of xylanases and glucanases improves the absorption and digestion of feed materials like barley-based feed and high-fiber rye for poultry and pig. Xylanase along with glucose oxidase, α-amylase, and malting amylase breaks down hemicelluloses in wheat flour, leavening the dough, increasing bread volume, making the bread softer, etc., aids in the bakery industry [7].

This review focuses on the real-world application of xylanase along with xylanase-producing microbes. The main aim of this review is to incorporate almost all the xylanase sources along with their significance into a single sheet.

2. Methods

Article screening was carried out using different search engines viz. Hinari and PubMed. A six-year time frame was used for the accumulation of suitable articles. {(Xylanase) and (Microorganism)}, {(Xylanase producing microbes) and (enzyme activity)}, (Xylanolytic microbes), {(Xylanolytic microorganism) and (xylanase)}, are different keywords that have been used for article accumulation. While using keywords: ((xylanase) and (microorganism)), one hundred and eighty-eight search results had been shown in PubMed and five hundred and sixty-four search results had been shown in Hinari. Similarly, while using keywords: {(Xylanase producing microbe) and (enzyme activity)}, thirteen results had been shown in Hinari, and six results had been shown in PubMed; while using keywords: (xylanolytic microbes), twenty results had been shown in Hinari and thirteen results had been shown in PubMed; while using keywords: {(xylanolytic microorganism) and (xylanase)}, forty-three search results appeared in the Hinari search engine and twenty-one results in PubMed. Out of eight hundred and sixty-eight search results, one hundred and twenty-seven articles were selected for writing this review article.

The screening was carried out; duplicate articles along with irrelevant articles were discarded, and the available relevant contents were incorporated into this review paper. Microbial sources and real-world application of the xylanase were collected from screened primary, secondary, and tertiary sources data, i.e., original work data, review work data, e-books, etc. Articles containing the sources and application of xylanase were selected, collected, analyzed, and summarized in this review. Relevant data were summarized in a narrative way herein.

2.1. Classification of Xylanase. Within this classification system, xylanases are normally reported as being confined to families 10 (formerly) and 11 (formerly G). However, it is revealed that enzymes with xylanase activity are also found in families 5, 7, 8, 16, 26, 43, 52, and 62 [4].

Higher molecular weight and peptide-linked catalytic domain with a cellulose-binding domain falls under Family 10 while the enzyme with a lower molecular weight falls under Family 11. Based upon iso-electric points, Family 11 enzymes are subdivided into the alkaline and acidic groups. enzyme structure, mode of action, physiochemical properties, and substrate specificity are some of the differential factors in other families 5, 7, 8, and 43 [12]. Glyoside hydrolase (GH) families 5, 7, 8, 10, 11, 16, 43, 51, 52, and 62 have been reported to contain xylanase [4, 13].

Maximum activity of endo-xylanase has been observed in the pH range (4.0–6.5) at a temperature range (40–80)°C. The isoelectric point (pI) value of endo-xylanase produced from bacteria and fungi falls in the range of (4.0–10.3), with a molecular weight of a single subunit protein in the range (8.5–85) kDa [7].

For the hydrolysis of an unsubstituted region of arabinoxylan, the GH 11 xylanase family is suitable while GH 10 xylanase family is suitable for side-chain arabinose residuexylose linkage. The GH8 xylanase family is unique from other xylanase families as it acts only on xylan while GH5, GH7, and GH43 xylanase act on endo-glucanases, arabinofuranosidase, or licheninases. The enzymatic action of a novel endo-xylanase of the GH30 family has been reported for its specificity towards glucoronoxylan [14].

34 arabinoxylanase, a subfamily of 5 glycoside hydrolase, requires some furnishing for catalytical specificity for xylans (arabino-substituted) to generate reducing end-branched xylooligosaccharide. Enzyme catalysis of GH8 xylanase families is different from that of other GH families, as GH8

catalyzes via a net inversion mechanism while other GH family catalyzes via a retaining mechanism. Short xylooligosaccharide along with soluble and branched xylans are suitable for higher GH10 xylanase activity while insoluble xylan and unsubstituted regions of xylan are suitable for higher GH11 xylanase activity. The enzyme activity of GH 11 xylanase is lower in the case of furnished xylan. The methylglucuronic acid substation is mandatory for the enzyme activity of 8 xylanase, a subfamily of GH30 xylanase (glucoronoxylanase) [3].

2.2. Xylanase Sources. The availability of xylanase in both prokaryotes and eukaryotes has been reported. Documented evidence for xylanase production includes marine and terrestrial bacteria, rumen bacteria, protozoa, fungi, marine algae, snails, crustaceans, insects, and the seeds of terrestrial plants and germinating seeds. Information on xylanase production from plants and endo-xylanase from Japanese pear fruits during the over-maturing period has been reported. Along with this, higher animals such as Mollusca have been reported for xylanase production [2]. Ease of availability, higher volumetric productivity, structural stability, and ease of genetic manipulation are the reasons behind the preference for microbial sources over plants and animals [11].

Micrococcus, bacillus, paenibacillus, staphylococcus, cellulomonas, microbacterium, arthrobacter, rhodothermus, and pseudoxanthomonas are bacterial genuses that have been reported for xylanase production. Nonomuraea, Streptomyces, and Actinomadura are some actinomycetes reported for xylanase production. Malbranchea sp. Thermoascus auranticus, Chaetomium thermophilum, Humicola insolens, and Melanocarpus sp. are fungi genera that have been reported for the production of alkaline stable xylanase. The industrial processes operated at higher pH are the reason behind the benefit of bacterial xylanase over fungal xylanase, as bacterial xylanases have pH optimums in the neutral or alkaline range, while production of fungal xylanase requires additional steps due to the optimum pH in the acidic range [7].

Thermostable xylanase has been reported for production by various thermophilic bacteria belonging to genus *Geobacillus*, *Bacillus*, *Thermotoga*, *Thermoaner obacterium*, *Anoxybacillus*, and *Acidothermus* [15].

2.2.1. Bacterial Source. Bacillus species is the most potent xylanase producer among bacterial species which includes *Bacillus* sp., *B. halodurans*, *B. pumilus*, *B. subtilis*, *B. amyloliquefaciens*, *B. circulans*, and *B. stearothermophilus* (Table 1) [8].

2.2.2. Marine Source. *Halocynthia aurantium* and *Deroceras reticulatum*are marine invertebrates xylanase sources have been reported. *Bacillus tequilensis*, *Achromobacter xylanoxidans*, *Bacillus subtilis* cho40, and *Bacillus subtillus* SR60 are marine bacterial sources of xylanase. *Streptomyces olivaceus* (MSU3), *Streptomyces albidoflavus* SAMRC-UFH5, and *Verrucosispora* sp. K2-04 are marine actinomycetes sources of xylanase.*Aspergillus cf. tubingensis* LAMAI 31, *Bartalinia robillardoides* LF550, *Calcarisporium* sp. KF525; *Penicillium pinophilum* LF458, *Pestalotiopsis* sp. KF079, *Scopulariopsis brevicaulis* LF580, and *Tritirachium* sp. LF562 are marine xylanase-producing fungi [11].

2.2.3. Protozoa Source. *Entodinium* sp., *Diploplastron affine*, *Eudiplodinium maggii*, *Polyplastron multivesiculatum*, *Dasytricha ruminatium*, and *Epidinium caudatum*, rumen protozoans, have been reported for their xylanase activity [76].

2.2.4. Archer Source. *Pyrodictium abyssi*, *Pyrococcus furious*, *Sulfolobus solfataricus*, *Thermococcus zilligii*, and *Thermofilum strains* of hyperthermophilic archaeal microbes have been reported to produce thermostable xylanase [6]. Highly thermostable xylanase production via *Sulfolobus solfataricus* has been studied [44].

2.2.5. Fungal Source. Filamentous fungi, particularly *Aspergillus* and *Trichoderma* are well known for the effective production of xylanolytic enzymes [96]. Xylanase-producing fungal sources are summarized in Table 2.

2.3. Real-World Application of Xylanase. Multifaceted applications of xylanase have driven research activities around the globe over the past few years. The real-world application arena of xylanase includes biofuel production, pulp and paper industry, baking and brewing industry, food and feed industry, and deinking of waste paper [7]. Xylanase has been reported to be used in various industries in a combined form with other enzymes which include cellulase, agarose, pectinase, amylase, phytase, hydrogenase, sucrase, β-glycosidase, polygalacturonase, FPase, CMCase, α-amylase, cellobiohydrolase, and Lytic polysaccharide monooxygenase, for synergistic activity [17].

The real-world applications of xylanase in the different arenas are discussed below.

2.3.1. Pharmaceutical Industry. Xylanase, being a hydrolytic enzyme, catalyze the hydrolysis of xylan and leads to the formation of hydrolytic products, xylooligosaccharides (XOS) [124]. Xylose is a monomer unit of XOS. Application of XOS in the biotechnology, pharmaceutical, food, and feed industries has been reported. Gastrointestinal tract absorption and hydrolysis are absent and have been reported to play a vital role as prebiotics. Selectively stimulate gastrointestinal microorganism growth, indicating the regulation of human digestive health [8]. *Bifidobacteria,* a healthy human gut bacteria growth promotion by the use of enzymes has been reported. Ferulic acid along with hydroxycinnamic acids, by-products of xylanolytic enzymes which are the hydrolytic products of xylan hydrolyzed by feruloyl esterase

Table 1: Documented xylanase-producing bacterial sources.

Bacterial list	Reference
Bacillus pumilus (BS131); *Bacillus safensis* (BS37); *Bacillus cereus* (BS1); *Bacillus altitudinis* (BS2); *Bacillus amyloliquefaciens* (BS6); *Staphylococcus warneri* (BS35); *Providencia rettgeri* (BS5)	[16]
Bacillus amyloliquifaciens; *B. sonorensis*; *Clostridium stercorarium*; *Pseudomonas* sp. GO2; *Serratia rubidaea* DBT4; *Aneurinibacillus*: Zymomonas mobilis; Thermobacillus xylanilyticus	[17]
Bacillus circulans; *Thermotoga maritime*	[18]
Geobacillus sp. strain DUSELR13; *Geobacillus stearothermophilus*; *Geobacillus thermodenitrificans*; *Geobacillus* sp. strain WSUCF1; *Geobacillus thermolevorans*; *Geobacillus stearothermophilus* sp. strain XT6; *Geobacillus stearothermophillus*strain KIGBE-IB29; *Bacillus altitudinis* strain DHN8; *Anoxybacillus flavithermus* strain TWXYL3; *Bacillus pumilis* SV-85S; *Geobacillus thermodenitrificans* A333; *Actinomadura geliboluensis*; *Geobacillus thermodinitrificans strain* NG80-2 XynA2; *Geobacillus* sp. strain TF16	[15]
Pseudomonas mohnii; *Pseudomonas* sp. WLUN024; *Pseudomonasboreopolis*; *Pseudomonascellulose*, *Pseudomonasboreopolis*G22; *Bacillus subtilis*ATCC 6633; *Bacilluslicheniformis*A99; *Bacillus subtilis*; *Bacillus coagulans* BL69; *Bacillus subtilis* BS04; *Bacillus megaterium* BM07; *Geobacillus stearothermophilus* KIBGE-IB29; *Cellulomonas flavigena*PN-120	[19]
Brevibacillus Borstelentis (MTCC 9874)	[20]
Cellulomonas flavigena DSM 20109T; *Bacillus*altitudinis 41KF2bT; *Bacteroides succinogenes*; *Cellulomonas flavigena*; *Ruminococcus flavefaciens*; *Rumninococcus albus*	[21]
Bacillus agaradhaerens	[22]
Maribacter sp. T28	[23]
Paenibacillus sp. (S150)	[24]
Bacillus subtilis strainTD160 (229);	[25]
Bacillus sp. BA N P3.3; *Bacillus* sp. MM P2.8; *Bacillus* sp. BA N P1.4; *Bacillus zhangzhouensis* MCCC 1A08372	[26]
Paenibacillus polymyxa NMA1017	[27]
Bacillus subtilis ATCC 6633; *Bacillus mojavensis* A21; *Bacillus* spp. Lb-4; Streptomyces sp. Ab106; Streptomyces albus; Streptomyces chromofuscus; Streptomyces viridosporus T7A	[28]
Bacillus licheniformis (strain NZYM-CE)	[29]
Bacillus subtilis (strain LMG S-27588)	[30]
Thermotoga caldifontes	[31]
Thermoanaerobacter italicus; *Thermoanaerobacterium aotearoense*	[32]
Paenibacillus popilliae NBM68; *Paenibacillus* sp. N1; Cellulosimicrobium cellulans CKMX1; *Paenibacillus ehimensis* NBM24; *Thermobacillus* sp NBM6	[33]
Geobacillus thermoleovorans; *Bacillus halodurans* S7; *Bacillus halodurans* TSEV1; *Microcellaalkaliphila* JAM-AC0309; *Geobacillus thermodenitrificans*TSAA1; *Acidothermuscellulolyticus* 11B; *Cellvibrio mixtus* (AF049493); *Bacillussp.* N16-5; *Thermobifidafusca*; *Thermoanaerobacterethanolicus*; *Thermotogamaritima*	[34]
Jonesia denitrificans; *Gracilibacillus* sp. TSCPVG; *Rhodothermus marinus*DSM 4252	[35]
Bacillussp EM24; *Bacillussafensis* LBF P20; *Bacillussubtilis* LBF M8; *Bacillus pumilus* PU4-2	[9]
Herbivoraxsaccincola A7 and GGR1	[36]
Stenotrophomonassp. EL-8; *Halomonasmeridian* NBRC 15608; *Bacillus safensis* P20; *Acinetobacterbaumannii*; *Stenotrophomonassp.*; *Streptomyces drozdowiczii*	[37]
Caldicoprobactersp. CL-2; *Caldicoprobacter faecale* DSM 20678T	[38]
Bacillussubtilis LMG-S 15136	[39]
Bacillusamyloliquefaciens CBS 143954	[40]
Bacillus subtilis CBS 143946; *Bacillus amyloliquefaciens* (ATCC 3978); *Bacillus subtilis*(ATCC 2107)	[41]
Bacillussubtilis LMG S-27588	[42]

Table 1: Continued.

Bacterial list	Reference
Paenibacillus polymyxa CKWX1; *BacillusSam-3; Bacillussp.* AB16; *Bacillussp.* AB-16; *Bacillussp.* 41-M; *Bacillus circulans* D1; *Bacillussp.* SPS-0; *Bacilluspumilus* SSP-34; *Cellulomonasflavigena* Xyl53; *Cellulomonas flavigena* Xyl36; *Streptomyces olivaceoviridis* E-86; *Streptomyces* T-7; *Streptomyces* sp. QC-11-3; *Streptomyces rameus* L2001; *Streptomyces cyaneus* SN32; *Streptomyces matensis* DW67; *Actinomadura* sp. Cpt20; *Thermobifida halotolerans* YIM 90462T; *Bacillus pumilus* SSP 34; *Nesterenkonia xinjiangensis* CCTCC AA001025; *Enterobacter* sp. MTCC 5112; *Clostridium acetobutylicum*; *Penicillium purpurogenum;Streptomyces cyaneus* SN32	[2]
Clostridium thermocellum; *Acetivibrio cellulolyticus*; *Bacillus thermoamylovorans* 1141; *Geobacillus thermodenitrificans* 3781	[43]
Caldicoprobacter algeriensis; *Geobacillus* sp *Strain* WSUCF1; *AcinetobacterJohnsonii*	[44]
Penibacillus curdlanolyticus B-6	[45]
Petrimonas mucosa	[46]
Clostridium sp. PXLY1; *Flavobacterium frigidarium*; *Bacillus mojavensis* AG137; *Stenotrophomonas maltophila*; *Rhodothermusmarinus*; *Pediococcus acidilactici* GC25	[7]
Aneurinibacillus aneurinilyticus DBT87; *Bacillus cereus* DBT10; *Serratia liquefaciens*; *Bacillus licheniformis* strain JK7	[47]
Paenibacillus xylanivorans	[48]
Bacillus tequilensis	[49]
Bacillus nealsonii	[50]
Thermoanaerobacterium sp. M5	[51]
Cellulomonas fimi B-402	[52]
Proteus mirabilis; *Bacillusmegaterium*	[53]
Bacillus subtilis SK4082; *Bacillus amyloliquefaciens* SK4079	[54]
Bacilluslicheniformis KCCM 43270	[55]
Geobacillus vulcani GS90; *Geobacillus galactosidasius* BS61	[56]
Roseithermussacchariphilus	[57]
Bacillussubtilis ADI1	[58]
Paenibacillus sp. AR247	[59]
Bacillussp. MCC2728; *Bacillus* sp. MCC2727	[60]
Bacillussubtilis subsp. *subtilis* JJBS 250	[61]
Bacillus pumilus IMAU80221	[62]
Chromobacterium violaceum (NAIMCC-B-02276; MCC 4212)	[63]
Paenibacillus xylanivorans A57	[64]
Bacillus sp. Asc6BA; *Pyrodictium abyssi*; *Herbinix hemicellulosilytica*; *Thermotoga neapolitana*; *Caldicellulosiruptor owensensis*; *Nonomuraea flexuosa; Dictyoglomus thermophilum*	[65]
Arthrobacter sp. AGC01501.1; *Bacillus* sp. ACR47980.1; *Paenibacillus campinasensis* Q2I6W5; *Bacillus subtilis* P18429; *Paenibacillus curdlanolyticus* BAK22544.1; *Streptomyces hygroscopicus*	[66]
Bacillus licheniformis Alk-1; *Geobacillus* sp. TF16; Thermotoga sp. strain FjSS3-B; *Caldicoprobacter algeriensis* strain TH7C1; *Dictyoglomus thermophilum*; *Caldicoprobacter algeriensis* TH7C1	[6]
Bacillus arseniciselenatis DSM-15340; *Bacillus pumilus* GESF1; *Halomonas meridian*; *Thermoanaerobacterium saccharolyticum* NTOU1; *Zunongwangia profunda; Glaciecola mesophila* KMM241; *Bacillus mojavensis* PTCC 1723; *Vibrio* sp. strain AX-4	[11]
Bacillus safensis NPUST1	[67]
Thermotoga maritime MSB8; *Cellvibrio mixtus* Xyn10B	[68]
Bacillus subtilis SR60; *Fictibacillus* sp. YS-26	[69]
Bacillus subtilis strain LMG S-27588	[70]
Reticulitermes santonensis	[71]
Caldicellulosiruptor bescii; *Anoxybacillus kamchatkensis*; *Streptomyces lividans*	[72]
Pseudomonas putida; *Paenibacillus xylanexedens* (MF347934); *Clostridium hiranonis* (NR_028611); *Anoxybacillus gonensis* (CP012152); *Actinobacter lwoffi* (NR_113346); *Caulobacter Segnis* (NR_074208)	[73]
Bacteroidales bacterium KA00344	[74]

Table 1: Continued.

Bacterial list	Reference
Geobacillus sp. MT-1; *Bacillus halodurans* C-125; *Xanthomonas campestris* pv; *Cellvibrio japonicas*; *Streptomyces coelicolor* A3	[75]
Deltaproteobacteria sp.; *Epsilonproteobacteria sp.*; *Clostridiales sp.*; *Bacillaceae sp.*; *Methylococcaceae sp.*; *Pasteurellaceae sp.*; *Verrucomicrobiaceae sp.*	[76]
Pseudoalteromonas haloplanktis	[77]
Bacillus aestuarii UE25	[78]
Thermoanaerobacterium thermosaccharolyticum; *Thermoanaerobacter brockii* HTD4; Thermoanaerobacterium sp. R63	[79]
Streptomyces sp. S27 ACF57948.1; *Streptomyces coelicolor* NP_733679.1	[80]
Amycolatopsis sp. GDS	[81]
Pseudomonas congelans; *Pseudomonas orientalis*	[82]
Streptomyces favogriseus; *Streptomyces griseoaurantiacus* (GenBank accession number MN581664)	[83]
Streptomyce viridochromogenes	[84]
Clostridium thermocellum B8	[85]
Bacillus sp. BMP01; *Bacillus amyloliquefaciens* XR44A	[86]
Prevotella ruminicola	[87]
Thermothelomyces thermophilus LMBC 162	[88]
Bacillus subtilis RH5	[89]
Bacillus pumilus (strain BLXSC)	[90]
Bacillus methylotrophicus	[91]
Bacillus subtilis strain DP-Ezd31	[92]
Thermobifida fuscaGenBank AAZ56956.1	[93]
Bacillus altitudinis RSP75 MW559543; *Bacillus tequilensis* G9 KR866144	[94]
Aeromonas punctate	[95]

Table 2: Documented xylanase-producing fungal sources.

Fungi list	Reference
Trichoderma reesei; *Trichoderma pleuroticola*; *Trichoderma atroviride*; *Paecilomyces themophila* J18; *Trichoderma aculeatus*; *Trichoderma atroviride* 3.3013	[96]
Paecilomyces varioti; *Thermomyces lanuginosus*; *Malbranchea cinnamomea* strain S168; *Chaetomium thermophilum*	[6]
Sugiyamaella halophilus strain SSA-1575T; *Sugiyamaella xylanolytica*; *Sugiyamella smithiae* SSA-1590T; *Candidagotoi*; *Candida pseudorhagii* SSA-1542T; *Hamamotoa lignophila* SSA-1576T; *S. xylanicola* sp. nov.	[71]
Aspergillus sydowii Fsh102; *Fusarium oxyporum*; *Trichoderma viride* Fd18; *Aspergillus Niger* E-1; *Aspergillussydowii* SBS 45; *Aspergillus awamori* VTCC-F312; *Bispora* sp. MEY-1; *Aspergillus Niger* strain C3486; *Trichoderma inhamatum*; *Aspergillus sydowii* CBS 593.65	[72]
Schizophyllum commune; *Aspergillus usamii*; *Trichoderma lanuginosus* SSBP; *Penicillium occitanis* Pol6	[2]
Trichoderma longibrachiatum CBS 139997	[97]
Trichoderma reesei ATCC PTA-5588	[98]
Trichoderma citrinoviride IMI SD 135	[99]
Trichoderma reesei CBS 114044	[100]
Aspergillus oryzae DSM 26372	[39]
Aspergillus Niger CBS 109.713	[101]
Aspergillus Niger NRRL 25541	[100]
Aspergillus oryzae (DSM 10287)	[100]
Sporotrichum thermophile; *Myceliophthora thermophile*; *Myceliophthora thermophila* ATCC 42,464; *Myceliophthora thermophila thermophila* BJTLRMDU3; *Penicillium citrinum* MTCC 9620; *Penicillium chrysogenum* QML-2; *Aspergillus Niger* CECT 2700; *Trichoderma koeningi*; *Trichoderma stromaticum* AM7; *Aspergillus favus*; *Myceliophthora heterothallica* F.2.1.4; *Myceliophthora thermophila* BF1-7; *Aspergillus oryzae* LC1; *Sporotrichum thermophile* ATCC 34628; *Myceliophthora thermophila* C1; *Thermoascus aurantiacus* var. *levisporus*KKU-PN-12–1; *Aspergillus oryzae* MDU-4; *Stenocarpella maydis*; *Eupenicillium parvum*; *Tremella fuciformis*; *Aspergillus tubingensis* FDHN1; *Penicillium roqueforti* ATCC 10,110; *Trichoderma* sp. TP3-36; *Aspergillus tamarii Kita*; *Aureobasidiumpullulans* NRRL Y 2311-1; *Penicillium chrysogenum* F-15	[102]

Table 2: Continued.

Fungi list	Reference
Eupenicillium javanicum; *Aspergillus japonicus* PJ01; *Penicillium italicium* (MH856375); *Cladosporium angustiherbarum* (NR_152286); *Aureobasidium Leucospermi* (NR_156246)	[73]
Rhizopus oryzae UC2; *Aspergillus fumigatus* SK1; *Trichoderma asperellum* UC1	[103]
Aspergillus flavus (ZGCL17); *Penicillium digitatum* (ZGCL25); *Trichoderma harzianum* (ZGCL37)	[16]
Saccharomyces cerevisiae SCPW 17; *Cryptococcus adeliae*; *Cryptococcus flavus*	[104]
Rhizomucor miehei; *Remersonia thermophila* CBS 540.69; *Myceliophthora heterothallica* F.2.1.4. ; *Malbranchea flava*; *Pichia stipiti*	[74]
Phanerochaete chrysosporium	[105]
Bispora sp. MEY-1 ACS96449.1; *Neurospora crassa* Q7SDQ1; *Aspergillus* sp. Q4WG11.1; *Talaromyces cellulolyticus* BAO51921.1; *Penicillium* sp. ACY70400.1	[80]
Penicillium hirsutum; *Phoma* sp.; *Naganishia adeliensis* (formerly *Cryptococcus adeliensis*)	[106]
Penicillium oxalicum M1816	[107]
Neocallimastix frontalis; *Neocallimastix particiarum*; *Orpinomyces* sp.; *Olpidium* sp.	[76]
Pseudozyma hubeiensis STAG 1.7; *Hannaella pagnoccae* STAG 1.14; *Papiliotrema mangalensis* STAG 1.8; *Kodamaea ohmeri*TS21	[108]
Aspergillus terreus MS105	[78]
Aspergillus nidulans	[109]
Rhizopus sp.	[81]
Cadophora malorum; *Emericellopsis* spp.; *Pseudogymnoascus* spp.	[110]
Penicillium minioluteum N3C2; *Fusarium* sp. N6C6; *Cladosporium oxyporium* N1C1; *Mucor racemosus* N9C1;*Botryodiplodia* sp.; *F. velutipes*; *Botryotinia fuckeliana*CECT 20518; *Rhizomucor pusillus*; *Aspergillus awamori* IOC-3914; *Trametes versicolor*	[66]
Trichoderma camerunense; *Aspergillus terricola*; *Aspergill*us ochraceus	[111]
Trichoderma reesei strain RF5427	[112]
Verticillium dahlia; *Cochliobolus sativus*; *Pyrenophora tritici-repentis*; *Fusarium tricinctum*; *Penicillium cyclopium*; *Penicillium freii*	[113]
Papiliotrema laurentii SDBR-CMU-S1-02; *Rhodosporidiobolus ruineniae*; *Apiotrichum scarabaeorum*; *Aureobasidium melanogenum*; *Galactomyces* sp. S3-06	[114]
Rhizopus oryzae strain NRRL 29086; *Epicoccum nigrum* (MH102081); *Trichoderma paraviridescens*; *Penicillium brevicompactum*	[115]
Aspergillus luchuensisInui strain RF7398; *Aspergillus acidus* (strain RF 7398)	[116]
Penicillium canescens (PcXylA)	[117]
Talaromyces amestolkiae	[118]
Aspergillus oryzae strain NZYM-FA	[119]
Fusarium graminearum; *Acremonium cellulolyticus*; *Talaromyces versatilis*; *Penicillium chrysogenum* P33; *Talaromyces leycettanus*	[120]
Botrytis cinerea	[121]
Aspergillus giganteus; *Chaetomium trilateral*	[122]
Didymella strain 3.3; *Cladosporium* sp. strain 1.1	[123]

have been reported to show antimicrobial, anti-inflammatory, anti-diabetic, antithrombosis, anticancer, and cholesterol lowering agents [68].

Antiallergic activity, cytotoxic, laxative, and carbon source-promoting growth of probiotics are pharmaceutical applications of XOS that have been reported. By producing inhibitory compound action against IgE antibodies, anti-allergic activity was shown. Leukemia cells obtained from lymphoblastic leukemia, the cytotoxic activity of XOS has been reported during in vitro evaluation. It has been reported that severe constipation reduction with no side effects was seen in pregnant women after the consumption of XOS. Adjunct oral administration of XOS and rice husk has been reported to maintain gut microbiota, eventually regulating blood glucose, insulin resistance, and dyslipidemia. The pharmaceutical industry can use XOS for the preparation of hydrogels and coating materials for tablets [14].

2.3.2. Food Industry. Enzyme food technology is superior to conventional chemical food technology. The reduction in energy consumption, waste, by-products, along with environmental impacts are reasonable reasons to promote enzymatically processed food over conventional chemically processed food [68].

Most of the work carried out inside the bakery involves the use of arabinoxylans, the principle raw material of the baking industry. Wheat is essential for bread manufacturing and contains arabinoxylans in higher concentration [12].

The hydrolytic property of xylanase are capable of solubilizing unextractable arabinoxylan in water, which aids in the improvement of rheological properties, i.e., softness, extensibility, and elasticity by uniform water distribution and gluten network formation in the dough [8]. It also strengthens the dough and makes it capable of tolerating changes in process parameters and flour quality. Improvements in biscuit texture and taste have been reported after the addition of xylanase. Xylose is used for xylitol production and is a hydrolytic product of xylan hydrolyzed by xylanase. Xylitol can be used in food as a natural sweetener. Thus, it is beneficial for diabetic patients as a sugar replacement. Along with these applications, dental caries reduction properties have been reported as well [68].

Baking activities are carried out usually at a low to moderate temperature scales usually below 35°C. So, xylanase showing higher enzyme activity in this range is preferable for the baking industries. Microorganisms capable of facing unharmonious process parameters are suitable for the industrial preparation of xylanase. *Aspergillis* sp., *Trichoderma*sp., and *Bacillus* sp. have been reported to be used abundantly as sources of xylanase in the baking industry [125].

The use of xylanase is well known for improving the bread quality by increasing the bread volume, the use of recombinant xylanase from *Phoma* sp. MF 13 tested in Chinese steamed bread has shown a specific volume increment of 4.45%, chewiness of 25.2%, and hardness of 25.7%, concerning the controlled Chinese steamed bread sample [11].

2.3.3. Animal Feed. Monogastric animals, i.e., poultry, pigs, humans, etc., lack endogenous digestive enzymes for the digestion of cellulose and hemicellulose. To enrich the nutritional value of animal feed, exogenous enzymes such as xylanase, cellulase, phytase, ligase, etc., have been used [68]. Cereals, triticale, and soy-based diets have been reported as the most commonly used animal feeds [6]. Xylanase added to the feed can hydrolyze water-insoluble arabinoxylan, reducing the viscosity of the feed. Hence, it enhances the digestibility of the feed and aids in nutritional value [68].

Acidothermus cellulolyticus-produced endo-xylanase aids in the improvement of the nutritional value of poultry feed[12].

Avizyme® 1505 (endo-1,4-beta-xylanase, subtilisin, and alpha-amylase) [41], Beltherm MP/ML [42], Axtra® XAP 104 TPT(endo-1,4-beta-xylanase, protease, and alpha-amylase) [98], ECONASE® XT [100], HOSTAZYM® X [99], RONOZYME ® WX [100], RONOZYME® WX CT/L [126], Endofeed® DC(endo-1,3(4)-β-glucanase and endo-1,4-β-xylanase) [127], Natugrain® TS/TS L (endo-1,4-beta-xylanase and endo-1,4-beta-glucanase) [40] are some of the commercially produced feed enzymes.

2.3.4. Juice and Brewing Industry. The use of xylanase aid in the removal of polysaccharides such as cellulose, hemicellulose, starch, pectin, and surface-bound lignin by decreasing the viscosity and improving the quality of juice [128]. Clusters, along with undissolved solids and suspended materials can be removed via a purification process which includes centrifugation and filtration methods that aid in the improvement in clarity, aroma, and color of the resulting juice. An increase in the amount of reducing sugar along with decreased turbidity of juice produced from kiwi, apple, peach, orange, apricot, grapes, and pomegranate using xylanase produced from *P. acidilactici* GC25 have been reported. *Streptomyce* sp. AOA40-produced xylanase was partially purified and used for the clarification of apple juice. *Streptomyces* sp.-produced xylanase used for clarification of orange, mousambi, and pineapple, resulting in an improvement in clarity by 20.9%, 23.6%, and 27.9%, respectively [8].

Xylanase is used in combination with pectinase, amylase, and cellulase in the brewing and fruit juice industry. In the brewing industry mashing of barley, wheat, rye, sorghum, corn, and rice are mashed during the brewing process to make malt which is needed for releasing the malting enzyme required for fermenting starch into alcohol. The cell wall of cereals used in the brewing process contains nonstarchy polysaccharides along with pectins, increasing the energy expenditure along with less smooth malt production. To overcome this macerating enzymes, i.e., xylanase along with cellulase and pectinase is used. The use of these macerating enzymes results in the release of hydrolysable ingredients, i.e., sugar, minerals, pigments, phenolic compounds, other nutrients, and aroma. Other beneficial outcome includes an increment in yield, stability, and a decrease in the viscosity and haze of juice and wine [17].

Novozyme 188, Celluclast 1.5L, Sihazyme extro, Trenolin, Lallzyme Ex-V, Crystalzyme Tinto, Rohapect VR-C, Vinozyme G, Extrazyme, Extrazyme fruit, Extrazyme Blanc, Enzeco® cellulase CE-2, CEP, Enzeco® xylanase S, and Enzeco® hemicellulase are well known commercial enzyme products that have been reported to be used in juice and wine industry [17].

2.3.5. Pulp and Paper Industry. Xylanase enzyme aids in the bio-bleaching, bio-deinking, and bio-pulping processes of the pulp and paper industry. Cellulose and Lignin-linked xylan of pulp fiber upon enzymatical hydrolysis by pH and temperature-dependent xylanase aid in the brightening of pulp, an increase in bonding force, and the strength of paper. The production of flexible solar cells from xylanase bio-bleached pulp is capable of having a higher storage capacity [8].

Bacillus stearothermophillus and *Bacillus pumilus* produce alkali-tolerant xylanase capable of showing enzymatic action at higher temperatures and pHs and are suitable for use in the paper and pulp industry [12].

Printed paper is reused after recycling by removing the ink. Though reusing by recycling is a convenient method for pollution reduction along with need fulfillment, the use of chemicals such as chlorine or chlorine-based derivatives, ClO^-, NaOH, $NaCO_3$, H_2O_2, and Na_2SiO_2 increases the processing cost, energy, and is baleful for the environment. The use of enzymes during recycling aids to overcome it.

Table 3: Brand list of commercially-produced xylanase.

Commercial brands	References
Bleachzyme (Biocon, India), Cartzyme (Sandoz, US), Cartzyme MP (Clarient, UK), Ecozyme (Tomas Swan, UK), Irgazyme 10 A & Irgazyme 40–4× (Genercor, Finland), Ecopulp (Alko Rajamaki, Finland), VAI xylanase (Voest Alpine, Austria), and Rholase 7118 (Rohm, Germany), Sanzyme, and Albazyme-10A (Ciba Giey, Switzerland), Amano 90 (Amano pharmaceutical co. Ltd, Japan)	[8]
Belfeed B MP/ML (Belfeed, Belgium)	[39]
Beltherm MP/ML	[42]
ECONASE® XT	[100]
HOSTAZYM® X	[99]
RONOZYME® WX	[100]
RONOZYME® WX CT/L	[126]

Table 4: Brand list of commercially-produced xylanase in combination with other enzymes.

Commercial brands	References
Avizyme® 1505 (endo-1,4-beta-xylanase, subtilisin, and alpha-amylase)	[41]
Axtra® XAP 104 TPT (endo-1,4-beta-xylanase, protease, and alpha-amylase)	[98]
Endofeed® DC (endo-1,3(4)-β-glucanase, and endo-1,4-β-xylanase)	[127]
Natugrain® TS/TS L (endo-1,4-beta-xylanase, and endo-1,4-beta-glucanase)	[40]

Bacterial alkalophilic xylanase along with laccase results in an increment of the brightness of old newsprint pulp by 21.6%, inject print pulp by 4.1%, laser print pulp by 3.1%, magazine pulp by 8.3%, and Xerox paper pup by 1.9%. Reports regarding the improvement of the physical properties of old newspaper freeness by 17.8%, breaking length by 34.8%, burst factor by 2.77%, and tear factor by 2.4% have been reported [8].

The reduction of chlorine dioxide by 10% and chlorine by 20% during bio-bleaching of eucalyptus kraft pulp using xylanase produced from *Bacillus pumilus* have been reported [12].

2.3.6. Biorefinery Industry. Biofuel generation from lignocellulose biomass composed of cellulose (40–50) %, hemicellulose (xylan and others) (25–35) %, and lignin (15–20) % is carried out in three steps. Delignification, saccharification, and fermentation in the presence of yeast result in the production of bioethanol [17]. Xylanase assists in the pretreatment of agro-residue and saccharification of carbohydrate polymers to increase the sugar yield, eventually resulting in an increment in bioethanol yield [6].

Cellulomonas flavigena-produced xylanase Cfl Xyn11A was used for pretreatment of lignocellulose biomass resulting in an improvement in the yield of fermentable sugar required for bioethanol production. Lignocellulose biomass pretreatment done by enzyme cocktails (Xylanase, laccase, and cellulase) has been reported as a novel way for bioethanol production [7]. Coculture of *Geobacillus* sp. strain DUSELR 13 with *Geobacillus thermoglucosidasius* to produce ethanol by the enzymatic hydrolysis of lignocellulose biomass has been reported [15].

2.3.7. Textile Industry. Desizing, sourcing, and bleaching are the different processes involved in the textile industry. Alkali thermostable xylanase are used during the desizing and sourcing process. Desizing involves the adhering sizing material, sourcing involves whitening and absorbency improvement and bleaching involves imparting fixed standard whiteness to the fabric. The significance of enzymatic activity during processing is due to its specific action capable of removing hemicellulose impurity without loss in strength of the fiber. Snag regarding the commercialization of the enzymatic method is due to the hydrolysis of seed coat present within the fiber that may lead to the unwanted exposure to chemicals during the later stages i.e. bleaching and finishing [8].

Xylanase from *Bacillus pumilus* was used for enzymatic desizing of cotton and monopoly fabric.

Report demonstrating the bio-sourcing of jute fabric using xylanase produced from *Bacillus pumilus* ASH have been reported. Xylanase used along with surfactant like tween 80, EDTA shows significant improvement in fabric whiteness by 1.2%, brightness by 3.2%, and decrease in yellowness by 4.2%. *T. longibrachiatum* KT 693225-produced xylanase has been reported to show significant improvement in desizing, bio-sourcing, and bio-finishing without the addition of surfactant [8].

2.4. Commercial Xylanases. Commercially available xylanase brands are summarized in Table 3. Brand list of commercially produced xylanase in combination with other enzymes is listed in Table 4.

3. Conclusion

In this review paper, xylanase-producing sources along with the real-world application and some commercial products were presented which reflect the significance of this enzyme. To narrow down the subject matter for this review, optimized process parameters, an optimized substrate for higher enzyme production, and a detailed overview of the enzyme structure were not incorporated herein. Since much research work has been carried out due to their significance, this review could aid researchers around the globe by acknowledging researchers with multiple sources of xylanase along with its real-world application in a single sheet.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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