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SIGNIFICANCE & ROLE OF BIOTECHNOLOGICAL APPLICATIONS IN ENVIRONMENTAL & ENERGY SUSTAINABILITY IN PULP & PAPER INDUSTRY – AN OVERVIEW


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Abstract:

With increased emphasis on Sustainable Development Goals, Green Economy, Green Energy, Green Chemistry etc it has become imperative for the industrial sectors including pulp and paper to adopt appropriate green/ecofriendly technologies to reduce the energy and environmental footprint. In recent years, biotechnological application has gradually gained acceptability in pulp and paper industry in process operation as well as environmental management. Tailormade enzymatic applications or solutions are now available to reduce chemical consumption, energy consumption, slime formation etc during pulping and paper making process as well as improve product quality. Similarly improved microbial consortiums are now available which has not only reduced/eliminated the chemicals or nutrients requirement in conventional activated sludge process but has also reduced energy consumption required to decompose the organic matter leading to reduced operational costs. Similarly increased interest in installation of biomethanation plants by agro based paper mills can also be attributed to availability of improved microbial consortium with improved shock loading bearing capacity and improved performance efficiency in terms of pollution reduction and biogas generation. In context of RCF based kraft paper mills operating on Zero Liquid Discharge (ZLD), enzymatic applications can play a vital role in reducing the build-up of pollution load including VFA in closed loop as well reducing the Odor in product and environment as well as reduce adverse impact on product quality. To address to raw material shortage, biotechnological application in developing fast growing, high yield, disease resistant tree clonal plantations by R&D institutes as well as leading paper mills have already contributed not only in addressing raw material issues to a major extent but also has contributed significantly in promoting social/agro forestry leading to improvement in rural economy as well as green cover. Conversion of lignin, into value added products and biofuels is a potential area for biotechnological applications with lot of promise specially from circular economy point of view. The paper summarizes the biotechnology routes, techniques available as well as research being carried out in this area so as to contribute to making paper industry environmentally sustainable.

Key words: *Sustainable Development Goals, Green Economy, Green chemistry, Bio-pulping, Bio-bleaching, ZLD.*

Introduction:

As the focus on Sustainable Development Goals, Green Economy, Green Energy, and Green Chemistry intensifies, it's becoming crucial for industrial sectors, including the pulp and paper industry, to embrace suitable green and eco-friendly technologies. This shift is essential to minimize their energy consumption and environmental impact[1-2]. And, to mitigate the challenges, there is a growing need for sustainable and eco-friendly alternatives in the industry. Biotechnological applications particularly microbial and enzymatic applications, has emerged as a promising solution for a greener, ecofriendly technology to address energy and environmental issues. Microorganisms, such as bacteria, fungi, and actinomycetes, produce enzymes like lignin peroxidases, manganese peroxidases, laccases, and versatile peroxidases, which can efficiently break down lignocellulosic materials. Utilizing biological roots can offers advantages like reduced chemical usage, improved bleaching, enhanced paper quality, decrease in energy requirements and reduced operational costs. Enzymatic applications can play a vital role in reducing the build-up of pollution loads and in controlling odors in the product and the environment, while also preserving product quality. The advancement in high-rate biomethanation plants utilizing improved microbial consortia capable of handling shock loads more efficiently and enhancing pollution reduction and biogas generation. Another promising area for biotechnological applications in the pulp and paper industry is the conversion of lignin into value-added products and biofuels. This approach aligns with the principles of a circular economy, turning waste into resources and further reducing the environmental footprint of the industry. Furthermore, advancements in biotechnology have been crucial in developing fast-growing, high-yield, disease-resistant tree clones, addressing raw material shortages and boosting social/agro-forestry to a greater extent. In this paper, role of Biotechnology in the pulp and paper industry for addressing these challenges so as to contribute Sustainable Development Goals, reducing energy and environmental impact, Green Economy and Green Chemistry practices is reviewed.

Biotechnology for reducing environmental footprint in Pulp and Paper Industry

Biotechnological innovations by reducing the reliance on chemicals and energy can help in lowering greenhouse gas emissions and reducing the industry's carbon footprint.

Biopulping

Biopulping, the pre-treatment of wood chips with lignin-degrading fungi, especially white rot fungi (Fig. 1) such as Ceriporiopsis subvermispora, Trametes versicolor, and Phanerochaete chrysosporium, prior to pulping, significantly enhances the mechanical and chemical pulping processes. This technique improves the penetration and effectiveness of chemicals during the cooking of wood chips, facilitating the separation of cellulose fibers from lignin. Consequently, biopulping leads to reduced energy and chemical demands, improved paper quality, and a lesser environmental impact of pulp production. Fungi, particularly white-rot fungi, modify the lignin in wood cell walls, effectively "softening" the chips. This fungal pre-treatment can reduce the electrical energy requirements for mechanical pulping and yield stronger paper properties. It also

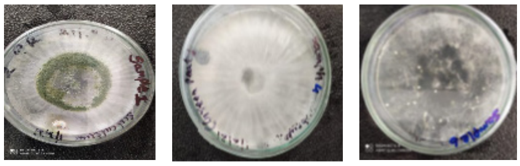


Figure 1: White rot fungi isolated for Biopulping

helps in reducing pollution load during various bleaching stages. The fungal pre-treatment is a natural process and is not expected to have adverse environmental consequences[3].

Studies have reported increased pulping yield with significant alkali savings and reduced energy consumption, demonstrating the efficiency and economic viability of biopulping. For example, the treatment of wood with Ceriporiopsis subvermispora, a white-rot fungus, has been shown to reduce the kappa number, which is a measure of lignin content in pulp, indicating effective delignification and potential for improved pulping processes3. These findings underscore the potential of biopulping as an energy-saving and environmentally friendly approach in the pulp and paper industry.

Trends in Biobleaching

Bio-bleaching presents several advantages, including reduced pre-bleaching operation costs, simple and inexpensive mill trials with minimal risk, reduced pollution from bleaching, decreased use of bleaching chemicals, potential to increase mill capacity, easy integration with traditional bleaching methods, and improved pulp physical properties. Research on the biobleaching utilizing extracellular xylano-pectinolytic enzymes from Bacillus amyloliquefaciens ADI2 revealed enhanced pulp attributes and reduced chlorine consumption, indicating an environmentally friendly biobleaching process[4]. A study utilized a novel fungal enzymatic cocktail, rich in xylanase and laccase, for the biobleaching of brown pulp have shown reduction in Kappa number and an increase in brightness[5]. Enzyme Cocktail for Bleach Enhancement where a combination of thermo-alkali-stable xylanase and mannase enzymes, derived from Bacillus species, was used for pulp biobleaching. This method resulted in significant reduction in Kappa number and increased brightness and whiteness[6]. These studies collectively demonstrate potential of biobleaching processes in the pulp and paper industry.

Enzyme-aided pulp and paper processing

Enzymes have become integral in the pulp and paper industry, offering a variety of processing benefits (Fig. 2). Microbial enzymes, including lipase, laccase, sterol esterase, and lipooxygenase, are effective in minimizing pitch-related problems, pulp dewatering, and

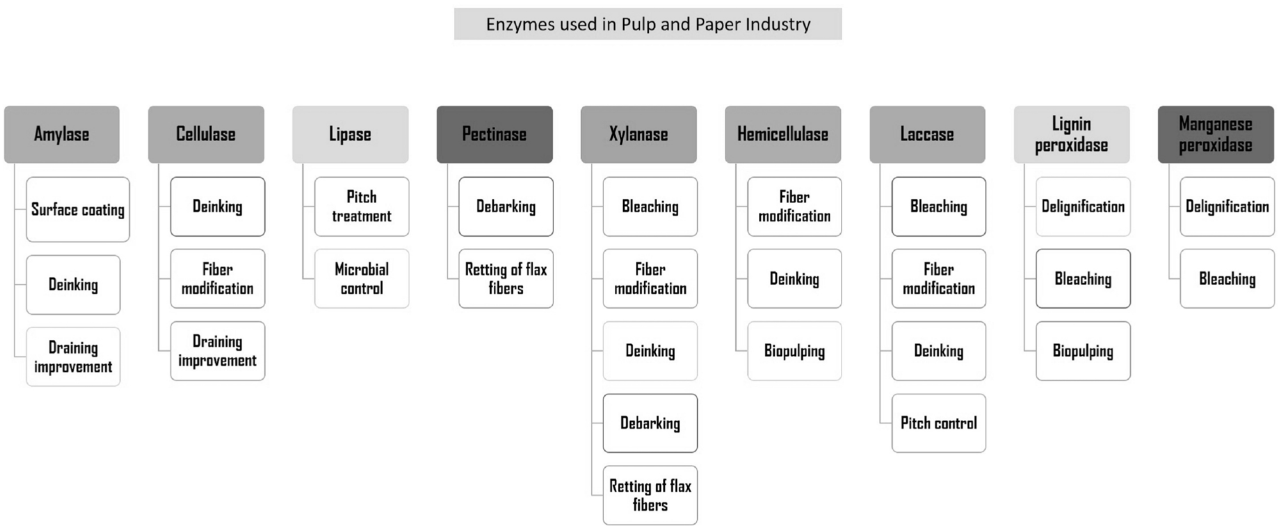


Figure 2: Enzymes used in the pulp and paper industry [10]

degradation of dissolved and suspended organics in concentrated mill effluents in the pulp and paper industry. They provide a green and clean alternative for various processes, including wood debarking and enzymatic retting[7].They also play a role in augmenting fibrillation for stronger paper production. These applications are propelled by the cost savings from reduced chemical and energy use, as well as the improved quality of the end products. Efforts are under progress to produce paper with desired properties through enzyme applications. Such as, the enzyme laccase can alter the hydrophobicity of fiber surfaces. A study showed that chitosan and laccase/phenols had a synergistic action in improving the hydrophobicity of pulp fibers. This approach is significant for enhancing the hydrophobicity and strength of papers through a green and biological method[8]. Endoglucanases have been utilized in pulp refining, reducing energy consumption and improving the mechanical properties of paper[9].

Biotechnological applications in Deinking of recycled fiber

Biodeinking, the use of enzymes for deinking purposes, is considered a potent and environmentally friendly approach. It offers a resource-saving and eco-friendly solution compared to the conventional chemical-based deinking process, with improved deinking efficiency and reduced environmental impact. Enzymes can facilitate dewatering of pulp and remove contaminants without reducing the strength of the recycled pulp fibers, leading to improved sheet formation and faster processing in paper machines. The enzymes hydrolyze some of the surface sugars on the pulp fiber, releasing the ink particles bound to the fiber. The ink is then removed through washing and draining of the pulp, followed by a conventional flotation step. This method eliminates the need for alkali treatment and subsequent bleaching with hydrogen peroxide, and any residual enzymes are deactivated during paper drying. Recent researches have shown that when deinking chemicals like NaOH, $Na2SiO3$, and $H2O2$ were replaced with enzymes during enzymatic deinking, it has shown an improvement in pulp freeness, decreased dirt count value. Physical strength properties such as burst index, tensile index, and double fold numbers were also improved during enzymatic deinking. Enzymatic deinking has been effective with old newsprint and office waste paper, and unlike conventional deinking, it efficiently removes laser printer and photocopier inks commonly found in office waste paper[11-13]. This enzymatic approach offers a more environmentally friendly and potentially cost-effective alternative to traditional chemical deinking processes.

Bioremediation and Biomethanation

To address the environmental issues, bioremediation and Biomethanation has been employed for treating industrial wastes, including those from paper and pulp mills. These technologies primarily rely on biodegradation, aiming to stimulate microbial consortia with nutrients and chemicals to destroy contaminants (Table 1). Researchers are actively identifying and testing new combinations of bacteria, fungi, and other microorganisms to create more efficient and robust consortia. Sometimes, this also involves algae and enzymes, either as a standalone treatment or in combination with physical and/or chemical methods. In pulp and paper mills, wastewater contains a variety of pollutants, including organic matter, chemicals used in the pulping process, and lignin derivatives. Traditional chemical treatments are often expensive and environmentally harmful. Microbial consortia provide a more sustainable and efficient alternative, capable of degrading and removing organic pollutants more effectively than single strains, thus reducing the need for chemical additives in the treatment process. By breaking down complex organic compounds, these consortia contribute to the reduction of pollution load in effluents, leading to cleaner wastewater with less environmental impact [14-15].

Biomethanation plants are increasingly recognized for their role in sustainable waste management and energy production, especially in agro-based paper mills. Biomethanation plants address challenges related to waste management by transforming waste into valuable biogas and biofertilizer through anaerobic digestion. Utilizing biogas for electricity or heat generation can significantly reduce a paper mill's dependency on external energy sources and lower energy costs. With advancements in microbial consortia, there has also been significant progress in the development of High-Rate Bioreactors. These modern bioreactors demonstrate superior performance compared to traditional biomethanation reactors, offering enhanced efficiency and effectiveness in processing [16]. Notably, these reactors, equipped with robust microbial consortia, exhibit versatility in operating across a wide range of pH and temperature conditions. Furthermore, they are designed for ease of commissioning, often beginning to yield results within a week, thereby offering a rapid startup and operational advantage.

ZLD in pulp and paper mills, especially those using RCF-based kraft paper processes, is a recent trrend for achieving sustainability and environmental compliance. Biological applications are essential in ZLD for enhancing wastewater treatment efficiency, reducing pollution load, odor control and slime build-up. These methods can include aerobic and anaerobic bacterial treatment, fungal treatment, or enzymatic treatment. Companies like Paque provides specific bioreactors which presents a cost-effective and technically viable solution for kraft paper mills utilizing ZLD. These biomethanation reactors enable the reutilization and recycling of backwater within a closed loop system to attain zero liquid discharge. This approach also involves the simultaneous co-generation of biogas and addresses the problem of odors. Strong odor from sulfur compounds and other volatile organic compounds can also be targeted by specific microbial enzymes which can break down these substances[18]. Enzymes like laccases and peroxidases from these fungi can break down residual lignin, while cellulases and hemicellulases aid in degrading cellulose and hemicellulose fragments. This enzymatic action reduces the molecular complexity of organic compounds, aiding their removal in subsequent treatment stages and enhancing water recycling efficiency[19].

Bacterial cellulose (BC): A Green Alternative for Plant Cellulose

BC is an eco-friendly nano-biomaterial that has garnered significant attention in the pulp and paper industry. Its structure is remarkably similar to plant cellulose, which contributes to its popularity. BC has potential applications in the paper industry, such as enhancing the strength of paper and increasing its water-holding capacity. Papers made from wood and agro-based raw materials generally possess limited barrier properties, restricting their use in packaging food or fluid materials. To improve these barrier properties for food packaging applications, BC can be used as an additive. Research indicates that the inclusion of BC, along with cationic starch (CS) at a very low dose of 0.8% (relative to CS), enhances the efficiency of CS as a dry strength additive in the wet-end of papermaking. This addition significantly improves breaking length, tear index, and burst index by 33.0%, 2.53%, and 63%, respectively, compared to papers made using only pulp. This study highlights the potential of BC as an additive for strengthening food packaging paper. These findings demonstrate the utility of BC in enhancing the physical properties of paper, particularly for food packaging applications, showcasing its role as a valuable additive in the industry 20-21.

Table 1: Bioremediation potential of microbes for metabolising Organic and Heavy Metal Pollutants

Bacterial species	**Organic pollutant**	**Heavy metal pollutant**
Bacillus spp.	Cresol, phenols, aromatics, long chain alkanes, phenol, oil-based paints, textile dye, sulfonated di-azo dye Reactive Red HE8B, Remazol navy blue dye	Cu, Zn, Cd, Mn
Pseudomonas spp.	Benzene, anthracene, hydrocarbons, polychlorinated biphenyl compounds	U, Cu, Ni, Cr, Cd, Pb, Zn, As
P. alcaligenes, P. mendocina, P. putida, P. veronii, Acinetobacter, Achromobacter, Flavobacterium	Petrol and diesel polycyclic aromatic hydrocarbons, toluene	-
Pseudomonas putida	Monocyclic aromatic hydrocarbons, e.g., benzene and xylene	-
Xanthomonas sp.	Hydrocarbons, polycyclic hydrocarbons	-
Nocardia sp.	Hydrocarbons	-
Streptomyces sp.	Phenoxyacetate, halogenated hydrocarbon, diazinon	-
Mycobacterium sp.	Aromatics, branched hydrocarbons benzene, cycloparaffins	-
Alcaligenes odorans, B. subtilis, Corynebacterium propinquum, P. aeruginosa	Phenol	-
Micrococcus luteus, Listeria denitrificans, Nocardia atlantica	Textile azo dyes	-
Acinetobacter sp., Pseudomonas sp., Enterobacter sp., Photobacterium sp., Bacillus spp., Staphylococcus sp.	Pesticides (chlorpyrifos, methyl parathion, malathion, endosulfan)	-
Rhodopseudomonas palustris, Aerococcus sp.	-	Pb, Cr, Cd
Citrobacter sp.	-	Cd, U, Pb
Lysinibacillus sphaericus	-	Co, Cu, Cr, Pb

Biotechnological roots to address fibrous Raw Material shortage

Biotechnological advances in the development of fast-growing, high-yield, and disease-resistant tree clones are significantly impacting the pulp and paper industry. The primary goal of this biotechnological research is to produce tree clones that grow faster, yield more pulp per hectare, and are resistant to diseases and pests. These characteristics are essential for meeting the increasing demand for paper products while minimizing the impact on natural forests and the environment22-23. Fast-growing tree species, including eucalyptus, poplar, and pine, are being genetically improved to accelerate their growth rates and increase wood density. This not only shortens the harvest cycle, allowing more frequent harvesting, but also ensures a higher yield of pulp per tree. Additionally, genetic modifications are being made to enhance the quality of the wood, making it more suitable for pulping and papermaking processes. For example, the potential of poplar phytochemicals as value-added co-products in a forest biorefinery context demonstrates the diverse applications of genetically improved tree species24. Disease and pest resistance are also key focuses of biotechnological research. Developing tree clones resistant to common diseases and pests reduces reliance on chemical pesticides and fungicides, which are harmful to the environment. These resistant clones are more likely to thrive in various climatic and soil conditions, increasing the resilience and sustainability of plantations[25-26].

Agroforestry combines agriculture and forestry practices to create more diverse, productive, and sustainable land-use systems. In the pulp and paper industry context, agroforestry involves growing tree species for pulp production alongside other crops, providing farmers with multiple income streams and improving land utilization. Many leading pulp and paper mills such as TNPL, ITC, Century P&P etc. taken up social and agroforestry at a large scale for developing clonal plantation of desired species. Biotechnological research supports these initiatives by developing tree varieties suitable for social and agroforestry systems, ensuring compatibility with local ecological conditions and agricultural practices.

Lignin Conversion and Circular Economy

The concept of a circular economy, which emphasizes efficient resource use, recycling, and minimizing waste, is particularly relevant in the pulp and paper industry. During the pulping process, lignin is separated from cellulose fibers and is often either burned for energy or disposed of as waste. However, advances in biotechnology and chemistry are changing this paradigm by enabling the conversion of lignin into a variety of valuable products. These value-added products include chemicals, materials, and bio-based polymers.

For instance, lignin can be converted into phenolic compounds, which are used in the production of adhesives, resins, and plastics. The development of lignin-derived carbon fibers for use in lightweight and high-strength materials is also gaining traction, with applications in industries such as automotive and aerospace. Lignin is also a potential source for the production of surfactants, dispersants, and as a feedstock for various chemical syntheses[27].

The production of biofuels is another promising avenue for lignin utilization. Lignin, abundant in aromatic compounds, can be converted into liquid biofuels such as bio-oil and biodiesel. These biofuels are renewable and can serve as alternatives to conventional fossil fuels, thereby reducing greenhouse gas emissions and dependence on non-renewable energy sources.

Developing efficient and cost-effective methods for converting lignin into biofuels is an active area of research. The challenge lies in dealing with the complexity and variability of lignin's structure, which affects its reactivity and the quality of the resulting biofuels. Advances in catalysis, genetic engineering, and process engineering are contributing to overcoming these challenges and improving the feasibility of lignin-based biofuel production[28-29].

CPPRI efforts in biotechnological application in P&P industry

CPPRI has also carried out R&D in the area of bio-bleaching, enzymatic refining, bio-deinking, bioremediation, BC applications and enzyme production which is summarized in brief as under:

- Works on evaluation of enzymes for response to bio-bleaching, enzymatic refining, bio-deinking, slimicide efficacy, Bioethanol production from lignocellulosic wastes, Ethanol estimation and Enzyme assisted re-pulping of wet strength papers. Bio-bleaching work at pilot scale by using xylanases have demonstrated 15% bleach chemical (chlorine and hypo) and 20-25% AOX reduction in bleach effluents.
- Research on cotton comber fiber refining using enzymes has been successfully demonstrated where Energy reduction of 15-20% during refining and strength property improvement in terms of tensile and double fold 6-12% and 20-30% respectively has been achieved.
- Enzymatic deinking studies using cellulase and xylanase have shown reduction in fines (15.4%), improvement in drainability (8.9%), improvement in brightness (0.9 units) and reduction in PC number (35.7 %).
- Bioremediation of paper mill effluent with indigenously developed microbial consortia has been demonstrated on pilot scale and improvement in lignin removal (15-33%), colour reduction (35-40 %), and AOX reduction by 20-30 % was achieved.
- Preliminary works on Bacterial cellulose production (Fig. 3) and its applications as additive in improving strength properties have shown improvement in breaking length, tear index, and burst index.
- Works carried out for screening of microbes for Laccase, MnP and Lignin peroxidase production (Fig. 4) so that it can be used for further research.

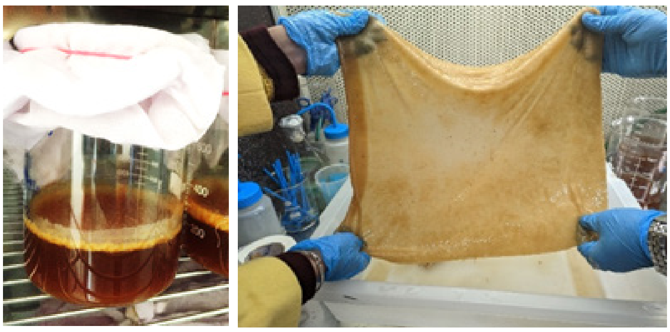
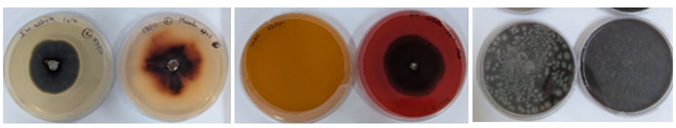


Figure 3: Bacterial cellulose production in CPPRI



(a) (b) (c)

Figure 4: Isolation of potential microbes for a) Laccase, b) MnP, c) Lignin peroxidase production in CPPRI

Conclusion and Future Prospects

The implementation of biotechnological solutions like enzymatic treatments, microbial consortiums, and genetic modification of tree species has led to considerable reduction in energy and chemical use, minimized waste generation, and enhanced the overall sustainability of the industry. These technologies help to address key challenges, including sustainable raw material sourcing, efficient waste management, and reduced environmental impact. Current research in the pulp and paper industry focused on enhancing sustainability, efficiency, and product quality through various biotechnological applications such as significant efforts are being made in the genetic modification of tree species to develop fast-growing, high-yield, disease-resistant clones that are more sustainable to cultivate and require fewer inputs. Microbial consortiums are another focus area, with research directed toward optimizing these communities for improving wastewater treatment processes and enhancing biogas production in biomethanation plants. The goal is to develop robust, efficient consortiums that can operate under industrial conditions, providing environmental and economic benefits. Developments are already in progress for conversion of lignin into value-added products and biofuels.

CPPRI efforts in various research areas, including bio-bleaching, enzymatic refining, bio-deinking, and bioremediation have shown notable results including reductions in bleach chemicals and pollutants, energy savings, improvements in paper properties, and effective microbial screening for enzyme production.

In conclusion, the roots of biotechnology are profoundly enriching the pulp and paper industry's journey towards sustainable growth. By harnessing the power of Biotechnology, this green revolution is remarkably slashing energy consumption and minimizing environmental footprints, paving the way for a cleaner, more efficient future

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