

Integrating Biotechnology and Circular Economy Principles for Sustainable Rural Handmade Paper Enterprises

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ABSTRACT

In the present scenario of rising pollution concerns and increasing episodes of environmental hazards or natural calamities, the relevance of biotechnology (BT) and circular economy (CE) has grown tremendously. There is a need for CE and sustainable production systems and how rural handmade paper (HMP) enterprises can be further improved for bringing sustainability. It highlights the potential of the HMP sector as a waste-to-wealth and resource-efficient production system that utilizes recycled fibres, agricultural residues and non-wood lignocellulosic biomass for papermaking. Whereas, CE can further enhance its sustainability. Although processing lignocellulosic biomass is challenging, biotechnology is a potential aid for overcoming these challenges through various applications. These applications highlight the actual potential of HMP enterprises which can serve as strong examples of grassroots rural employment with immense potential for incorporating CE principles along with BT.

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Need of Circular Economy and Sustainable Production Systems

Circular economy approach provides a pathway for the transitioning from conventional linear model of production and consumption towards minimize resource extraction, reduce waste generation systems. It also focuses upon retaining the value of materials and products for as long as possible. Rather than treating waste as an end product, the circular systems emphasizes on prevention, reuse, recovery, recycling and the reintegration of materials into production cycles. This approach can improve resource efficiency, reduce environmental pressure and increase the economic value of materials that would otherwise be discarded/thrown away as waste. In addition, circular economy strategies are associated with cleaner production, technological innovation and sustainable business models. Therefore, this results in supporting the integration of environmental and economic objectives within the production systems. (Geissdoerfer et al, 2017, Shahzabeen et al, 2023). Thus, the circular economy is an economic model that eliminates waste and pollution by keeping products and materials in continuous use. (Ellen

MacArthur). The framework for circular economy is shown in figure 1 (Magnus et al, 2018).

In the present scenario of rapidly increasing global population, there is an immense pressure of reducing resource consumption, waste generation and environment degradation. This has created an urgent need for the development of sustainable production systems. A transition from a “take-make-dispose” model towards resource-efficient, circular systems is therefore essential for reducing pressure on natural resources and improving environmental sustainability (Chauhan et al, 2025).

The pulp and paper industry is an important part of this transition because conventional papermaking depends majorly on wood. It involves energy-intensive processing operations. These processes significantly generate chemical, water and energy demands. Hence, the development of cleaner and alternative papermaking approaches has become increasingly important for the pulp and paper industry (Tripathi, 2017; Sun et al., 2018).

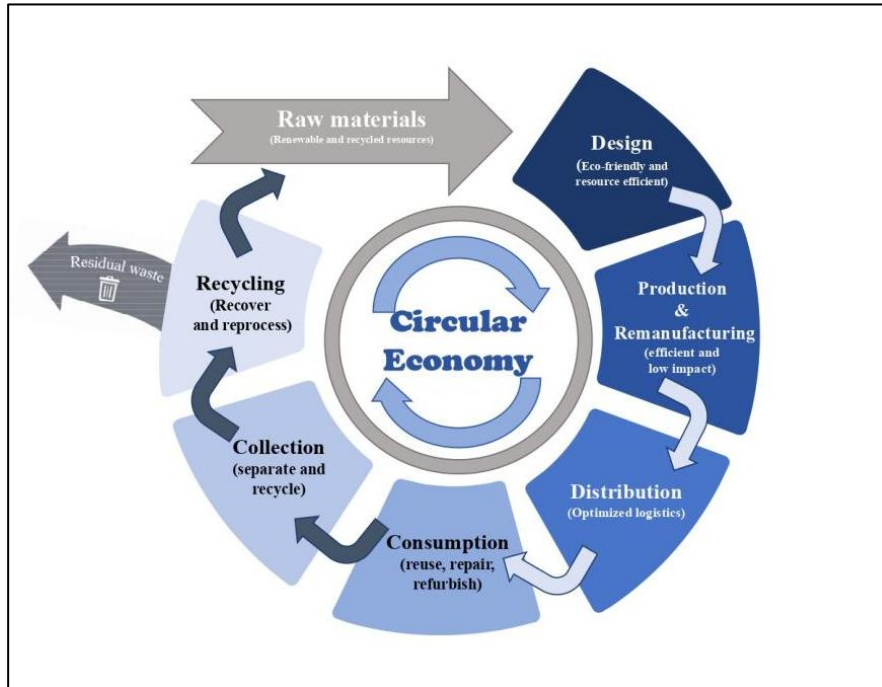


Figure 1 Circular economy framework

Handmade Paper Sector: A Sustainable Production System from its Core

As compared to the conventional mill papers, handmade papermaking has been a sustainable production system from its very core. It is an ancient art which has not only survived today but is also flourishing nicely with handsome contribution in earning foreign currency for the nation. It offers a promising sustainable alternative of the conventional mill made paper because it utilizes recycled fibres viz. cotton

rags/textile industry waste/tailor cuttings or different types of waste papers as principal raw materials besides using lignocellulosic waste biomass in the form of agro-residues, leaf fibers, bast fibers etc as alternative raw materials. Since utilization of such waste biomass converts otherwise low-value and waste streams into useful products, the sector has enough scope to support the principles of resource recovery and circular economy (Chauhan *et al.*, 2022; Alam *et al.*, 2018). The comparison between handmade paper and mill made paper is shown in table 1

Table 1 Handmade paper vs millmade paper

Parameter	Handmade paper	Mill-made paper	Reference
Raw materials	Recycled cotton/textile waste, waste paper, agricultural residues and non-wood fibres	Predominantly conventional woodbased fibres	Alam <i>et al.</i> (2018); Chauhan and Hussain, 2009
Production scale	Small-scale, decentralized and often artisan-based	Large-scale, centralized and highly mechanized	Jain & Gupta (2021); Thakker & Sun (2023)
Environmental approach	Strong potential for waste utilization and lignocellulosic waste biomass recovery	Highly dependent on conventional fibre and industrial processing	Chauhan <i>et al.</i> (2022); Goenka & Kulkarni (2026)
Employment generation	Labour-intensive; supports rural artisans and local enterprises	Highly mechanized with lower labour intensity per unit production	Chauhan and Hussain, 2009
Sustainability potential	Supports circular economy through recycling, reuse and waste-to-wealth approaches	High production efficiency but conventional processes requires more resource and chemicals	Chauhan <i>et al.</i> (2026)

History and development of handmade paper industry

The history of handmade paper is closely associated with the development of human communication and the use of renewable fibrous materials. Papermaking technology was reported to develop in China. It subsequently spread through Asia and Islamic nations before reaching to Europe (Hubbe

and Bowden, 2009). Yet, there are sufficient evidences to prove that the art of papermaking was well known to Indian subcontinent as early as 6th century BC (Teygeler, 1998, Bhattacharya, 2022, Chauhan and Singh 2000). Handmade paper was produced from bast fibres such as paper mulberry, hemp waste, old rags and fishnets. However, due to the religious beliefs, paper sheets were not considered

appropriate to record ancient scriptures in India. Therefore, paper like materials like papyrus, bhojpatras etc were used as writing surfaces. Later on, several technological developments like fixed-screen moulds, watermarks, printing technology and the Hollander beater in various parts of the world like Europe, Italy, Netherlands was developed (Neuman, 2023, Muller, 2023, Hubbe and Bowden, 2009). By the 18th and 19th centuries, mechanized and wood pulp based paper production expanded rapidly. It gradually displaced the traditional handmade papermaking in many regions (Jain and Gupta, 2021; Thakker and Sun, 2023).

In India, paper-making was a known science before the Mughal period. But, it remained relatively limited because palm leaves and other traditional writing materials were widely used. The industry expanded considerably during the Mughal period when paper became an important material for manuscripts, administration and trade. Several *kagzipura* or papermaking settlements were developed particularly in northern and western parts of India. Traditional Indian paper makers used waste based materials such as jute gunny bags, hemp ropes, nets and cotton rags. Thereby, demonstrating an early form of material recovery (Chettri 2019, Rezavi, 2014, Teygeler, 1998). The expansion of mechanized paper mills during colonial period weakened the traditional *kagzi* industry. A major revival occurred during the Gandhian period when the handmade papermaking was incorporated into the *Swaraj Andolan* (Freedom struggle movement) as a means of rural employment, self-reliance and sustainable production. Gandhi ji's initiatives encouraged the revival of handmade papermaking in Rajasthan, Gujarat, Maharashtra, Madhya Pradesh and Uttar Pradesh. (Teygeler, 1998; Jain and Gupta, 2021). The centres like Wardha, Kalpi and Pune promoted research, training and technological improvement. The establishment of KVIC in 1957, further supported raw-material supply, marketing, artisan training, technical improvement and diversification of handmade paper products. A further milestone was the establishment of the Kumarappa National Handmade Paper Institute (KNHPI) at Sanganer, Jaipur in 1997 subsequent to the successful implementation of United Nations Development Programme (UNDP)–Khadi and Village Industries Commission (KVIC) project. The institute was established to strengthen the handmade paper industry through research and development, technical services, training, consultancy and technological improvement. Since its establishment, KNHPI has contributed to the modernization, diversification and a continued development of this traditional rural industry. It is gracefully embedding circular economy principles that minimize waste and maximize resource efficiency.

Application of Circular Economy Principles to magnify the sustainability of Handmade paper sector

There are three basic principles of Circular Economy:

- Eliminate waste and pollution: Design products and production systems accordingly so that they minimize waste and pollution from the beginning.
- Circulate products and materials: Use the products for as long as possible through reuse, repair, recycling, refurbish and recovery.

- Regenerate natural systems: Use resources in such a way that it protects, restore and enhance natural ecosystems (Velenturf et al., 2021)

The decentralized structure of HMP sector is comparatively simpler and easy to adopt at various levels due to the utilization of locally available waste biomass as raw materials and thus creating sustainable rural production systems (Bhodiwal et al., 2022; Chauhan et al., 2022). The circular economy potential of handmade paper extends beyond fibre recovery. Waste materials can pass through a localized chain of collection, segregation, fibre preparation, papermaking, value addition, product utilization. This creates an economic value at multiple stages. Thus, handmade papermaking can function as a waste-to-wealth model while simultaneously supporting decentralized livelihoods and rural entrepreneurship (Chauhan et al., 2026).

Implementation of above three basic principles of circular economy to the handmade paper sector can further enhance its sustainability. A sustainable use of waste biomasses for making handmade paper may help in reducing waste and pollution. Recycling of waste papers in the form of mixed office waste (MOW), shredded currency waste (SCW) (Chauhan et al., 2009), newsprint waste (NPW), magazine waste (MW) and processing of secondary fibers in the form of cotton rags/textile industry waste/denim waste etc helps in circulating the products and materials. The long shelf life of around 800-1200 years of the handmade papers produced from banana or jute fibers allows its prolonged use. The recycling potential of handmade paper is even greater than the mill made paper as it can be recycled up to 5-6 times as compared to the limitation of 2-3 times for recycling of mill made paper. So, the second principle of circular economy is also very easy to implement in this sector. Once the use of natural fibers is extended or encouraged extensively in the handmade paper sector and the mass usage of handmade paper is promoted, the huge contributions can be made towards the regeneration of natural systems because even a minor substitution of mill made papers with handmade papers may result into reduction of deforestation, global warming, ozone layer depletion and carbon foot prints.

Current status, significance and relevance of the Handmade Paper Industry

Handmade paper has evolved from a traditional cottage craft into a resource recovery based industry. Indian handmade papermaking usually utilizes cotton, hosiery waste, agricultural residues, recycled paper and other non-wood fibres rather than depending on wood based raw materials. This provides a route for diverting the otherwise discarded materials into value added products. It also supports rural and artisanal livelihoods. Handmade paper is particularly relevant to the circular economy because waste materials can be recovered, processed and converted into new paper products. Used handmade paper and paper products can also be recycled easily and efficiently. The 2026 case study of the Pune Handmade Paper Institute demonstrates the contemporary relevance. The cotton textile waste was converted into handmade paper through traditional

processes. Modern product design and marketing inputs helped in revival of the unit and expanded its commercial potential. The study also highlights continuous challenges like labour intensity, dependence on skilled artisans, obsolete machinery and the need for technological and infrastructural improvement (Goenka and Kulkarni, 2026; Jain and Gupta, 2021).

Latest technological developments in handmade paper

Recent development in HMPI is directed towards combining traditional papermaking with improved raw material utilization, process optimization, resource recycling, biotechnological applications and product innovation. The search for alternative non-wood fibres has expanded to agricultural residues, banana fibre, water hyacinth, coffee pulp, aquatic plants, textile waste and other unconventional cellulosic resources (Thakker and Sun, 2023). Along with these, process improvement like shredding and mechanical preparation of waste, water-recycling systems, improved sheet handling and drying and selective introduction of machinery into labour intensive operations have taken place. The 2026 Pune study particularly supports a hybrid model in which traditional manual papermaking is retained. Also, modern design, product development, machinery and marketing are incorporated with traditional processes to improve efficiency, scalability and commercial viability (Goenka and Kulkarni, 2026). Biotechnology represents a further emerging technological direction through bioretting, biopulping, enzymatic biobleaching, biological effluent treatment, conversion of waste effluents into biofertilizers and microbial pigments (Chauhan et al. 2013, Aswal et al. 2020, Rajput et al. 2024, Chauhan et al. 2015, Satyanarayana et al. 2025, Chauhan et al. 2022). These approaches can complement traditional HMPI operations by improving fibre processing, reducing process severity and creating value from waste streams.

Biotechnology as a step further towards improving sustainability of the Handmade paper sector

Although circular economy principles can be implemented to improve the sustainability of handmade paper sector but there are certain limitations of process methodologies especially in view of the type of the raw material used for making handmade paper. As far as the traditionally used principal raw materials viz. cotton rags are utilized, the production process involves basic steps of sorting, chopping, beating, sheet making, pressing, drying and cutting. All through these steps, use of chemicals is almost negligible except the sizing (for writing printing grades) chemicals. But once the alternative raw materials including lignocellulosic waste biomasses are introduced, use of pulping and bleaching chemicals becomes essential thereby questioning the ecofriendly credentials of the handmade paper sector. Therefore, Biotechnology emerges as a wonderful solution to this problem.

Biotechnology is the use of biological systems, living organisms or their derivatives to develop products and technologies that can improve human health and environment. At its core, it harnesses the biomolecular processes to solve various problems in medicine, agriculture, industry and environment management. Biotechnological processes are generally less energy intensive and can operate under mild and controlled laboratory conditions. It utilizes naturally occurring organisms and enzymes for the conversion of raw materials into useful products. This biological approach reduces the dependence on harsh chemical processes thereby minimizing the generation of harmful by products. Biotechnology supports resource conservation and reduces environmental impact by utilizing renewable resources efficiently by incorporating them with biological systems. Therefore, the integration of biotechnology into industrial processes provides a sustainable and environment friendly approach in sustainable production system (Figure 2).

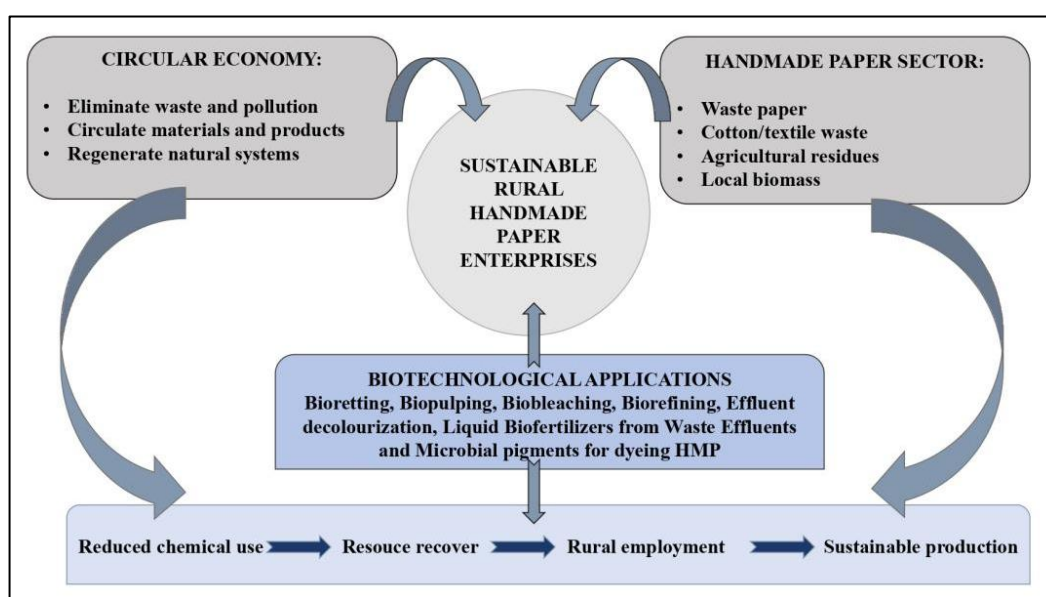


Figure 2 - Integration of Circular Economy and Biotechnology for Sustainable Rural Handmade enterprises

The proven Applications of Biotechnology for the Handmade Paper Sector

Bioretting

Bioretting is the process of removal of pectin, hemicellulose and other non-cellulosic materials from plant fibres with the help of microorganisms or their enzymes. Pectinolytic bacteria are particularly useful for this purpose. For example, xylanase-producing microorganisms have been used in jute retting to selectively remove hemicellulose (xylan) from the fibre bundles. *Das et al. (2012)* reported the use of *Bacillus* consortia with high pectinolytic and xylanase activities. They reduced the retting period from 19 days to 11-13 days while improving fibre strength and its fineness. Xylanase helps to remove non-fibrous hemicellulose without significantly affecting the cellulosic fibre (*Das et al., 2012; Hasan et al., 2020*). Bioretting can provide a cleaner alternative for the preparation of bast fibres used in handmade papermaking.

Work has been done on exploration of bioretting as a pretreatment for bast fibres (*Tahir et al 2011*). Selective removal of pectin and hemicellulose through bioretting can improve fibre separation and subsequent pulp processing. Such approaches can reduce dependence on prolonged conventional retting and improve the consistency of fibres used for handmade paper (*Lee et al, 2020, Chauhan et al, 2013*).

Therefore, bioretting is a relatively mild and environment friendly approach for fibre preparation. It can reduce retting time and improve fibre separation and fineness. The process may also reduce the need for harsh chemical treatments. However, microbial activity depends strongly on pH, temperature, moisture and incubation time. Maintaining uniform microbial growth and consistent fibre quality can be difficult at a larger scale.

Biopulping

Biopulping is the biological pretreatment of lignocellulosic raw materials before pulping. Fungi is commonly used for this purpose. It grows on the lignocellulosic raw materials and secrete lignin-degrading enzymes such as laccase, lignin peroxidase and manganese peroxidase. These enzymes selectively break down lignin and open up the fibre structure. Hence, subsequent pulping and refining is easier after treatment. Recent studies have demonstrated the potential of fungal biopulping for paper production from agricultural residues. *Moya et al. (2023)* used the white-rot fungus *Trametes versicolor* for biopulping pineapple leaf fibres (PALF). The process was followed by chemical bleaching and xylanase treatment. The combined process reduced the lignin content from approximately 12% to 4% and decreased the Kappa index from 27 to 13. Xylanase treatment further improved the brightness of the resulting paper. The study demonstrates that fungal biopulping can be integrated with enzymatic processing for converting agricultural residues into paper.

Aswal et al. (2020) investigated white-rot fungi for lignin degradation of *Calotropis procera* (Ankara) fibre. They identified promising fungal isolates for biopulping in handmade papermaking. White-rot fungi such as *Ceriporiopsis subvermispota* selectively degrade lignin and facilitate subsequent pulping. *Akhtar et al. (1997)* has reported that fungal pretreatment of *Pinus taeda* chips with *C. subvermispota* resulted in significant electrical energy savings during pulping. Biopulping has also been investigated for non-woody and agricultural residues. The process can reduce the severity of mechanical and chemical processing and improves the environmental performance of papermaking.

Therefore, biopulping can reduce lignin content and make subsequent pulping easier. It can lower the energy and chemical requirements of pulp processing and may improve fibre quality. The process also offers a more sustainable approach for utilization of non woody raw materials. However, fungal treatment generally requires longer incubation period and controlled conditions. Large-scale application and maintaining consistent fungal activity can be challenging for the conventional paper mill sector (due to its huge scale operations in continuous manner) but it can be easily incorporated into the small scale operations of batch processing of handmade paper production. The only need is to conduct dedicated research and studies in this area.

Biobleaching

Biobleaching is the use of microorganisms or their enzymes to reduce residual lignin in the pulp and helps in improving pulp brightness. It can reduce the requirement for conventional chemical bleaching agents and may operate under relatively milder conditions (*Chauhan and Bhatnagar, 2009*). A prominent example is biobleaching of paper mulberry pulp using the white-rot fungi *Phanerochaete chrysosporium* and *Pleurotus ostreatus*. The fungal treatment used played the role of bleaching agent and brightness increased about 13-14 points as compared to untreated pulp (*Chauhan et al., 2015*). Recently, *Rajput et al. (2024)*, reported biobleaching of Ankara pulp using a xylanase-producing bacterial consortium for sustainable handmade paper production. Xylanases and laccases are also widely used in reducing the chemical requirements of bleaching of pulp (*Chauhan et al 2006, Singh et al., 2019*).

Therefore, biobleaching can improve pulp brightness and reduces the use of conventional bleaching chemicals. Enzymes can act under relatively mild conditions and may reduce the environmental load of the bleaching process. It can also help in reducing residual lignin and improving pulp quality. However, enzyme activity depends on substrate, pH, temperature and dosage. High enzyme cost, limited stability and difficulty in achieving uniform treatment can be challenging for large scale application.

Biorefining

Biorefining is the process of use of enzymes to modify fibres before or during mechanical refining. Enzymes such as xylanases and cellulases can increase fibre flexibility,

fibrillation and water retention. Biorefining approaches have been explored to obtain multiple value added products from lignocellulosic biomass used in papermaking. *Mora et al. (2007)* demonstrated that how xylanase treatment produced structural changes in chemical pulp fibres and influenced its properties. Enzymatic treatment can therefore help in improving fibre development and reduce the intensity of mechanical refining. The enzymatic refining can help in saving beating energy to the extent of upto 20% while using denim waste or cotton rags as raw materials (*Chauhan et al, 2022*). Thus the process of biobeating/biorefining provides an opportunity to make beating more energy efficient.

However, biorefining can improve fibre flexibility, fibrillation and water retention but enzyme cost and treatment conditions need to be optimized for each raw material. Excessive enzymatic treatment may also affect fibre strength and drainage properties.

Biological Decolourization of Effluents

Microorganisms and their enzymes are used to remove colour producing compounds from papermaking effluents. White-rot fungi are particularly useful as they produce enzymes like laccase, lignin peroxidase and manganese peroxidase that helps in decolourization of effluents. Studies have reported the biological treatment of pulp and paper mill wastewater could reduce colour, COD, BOD and low molecular weight chloro lignins (*Bajpai and Bajpai (1994), Anju et al, 2018, Kumar et al, 2021*). At KNHPI, isolation and purification of white-rot fungal cultures has also been explored for the mycoremediation of handmade paper industry effluents (*Chauhan et al, 2015*)

Liquid Biofertilizers from Waste Effluents

Conversion of handmade paper waste effluents into liquid biofertilizers is an important example of biotechnology supporting circular economy to a massive extent. Recent studies have demonstrated the conversion of cowdungbased handmade paper effluents, particularly raw liquor (RL) and black liquor (BL) into liquid biofertilizers. *Satya Narayana et al. (2024)* showed that these waste liquors are potential as plant growth promoting inputs. Subsequent work demonstrated the effluent enriched with PGPR like *Azotobacter*, *Bacillus* and *Enterobacter* improve growth and yield of green chilli (*Capsicum frutescens*) (*Satya Narayana et al., 2024, 2025*).

Most recently, *Chauhan et al. (2026)* demonstrated that combining RL and BL with compatible microbial cultures like *Rhizobium*, phosphate-solubilizing bacteria, *Bacillus* and *Enterobacter* enhanced seed germination and growth of green gram (*Vigna radiata*). These examples supports the circular use of handmade-paper effluents as biofertilizer resources.

Microbial Pigments for Dyeing Handmade Paper

Microbial pigments are another potential biotechnology based route for colouring handmade papers. Bacteria and fungi produce pigments such as carotenoids, melanins, quinones and other secondary metabolites that can be used to colour handmade papers and textiles. *Rao et al. (2017)* reviewed about the wide range of pigments produced by bacteria and fungi and their potential as natural colourants. *Chauhan et al (2022)* presented work on “Microbial Pigments for Dyeing Handmade Paper”, highlighting the potential of biologically produced pigments for imparting colour to handmade paper. This approach can provide a renewable and potentially eco-friendly source of colour for value-added handmade paper products. These natural pigments can be explored for the development of naturally coloured handmade paper sheets. This may also reduce dependence on synthetic colourants. However, pigment production may vary with microbial strain and growth conditions. Limited colour stability, light fastness and scalability of pigment production are important challenges that require further optimization.

Role of KNHPI in Establishing the Linkage of Biotechnology for Handmade Paper Sector

Having realized the potential of Biotechnology, KNHPI had set up a Biotech lab of its own in the year 2002-03 and started the pioneering research work in the specific area. As a part of the exhaustive R&D and training activities at KNHPI, potentials of various biotechnological applications have been explored with an exclusive focus upon handmade paper industry (Figure-3). The encouraging results obtained have been presented before the scientific fraternity during various national and international conferences besides publishing in the scientific journals of repute. Some of the most useful and potent biotechnological applications include bioretting, biopulping, biobleaching, biorefining/biobeating, decolourization of effluents, liquid biofertilizers from the waste effluents and microbial pigments for dyeing the handmade paper sheets.

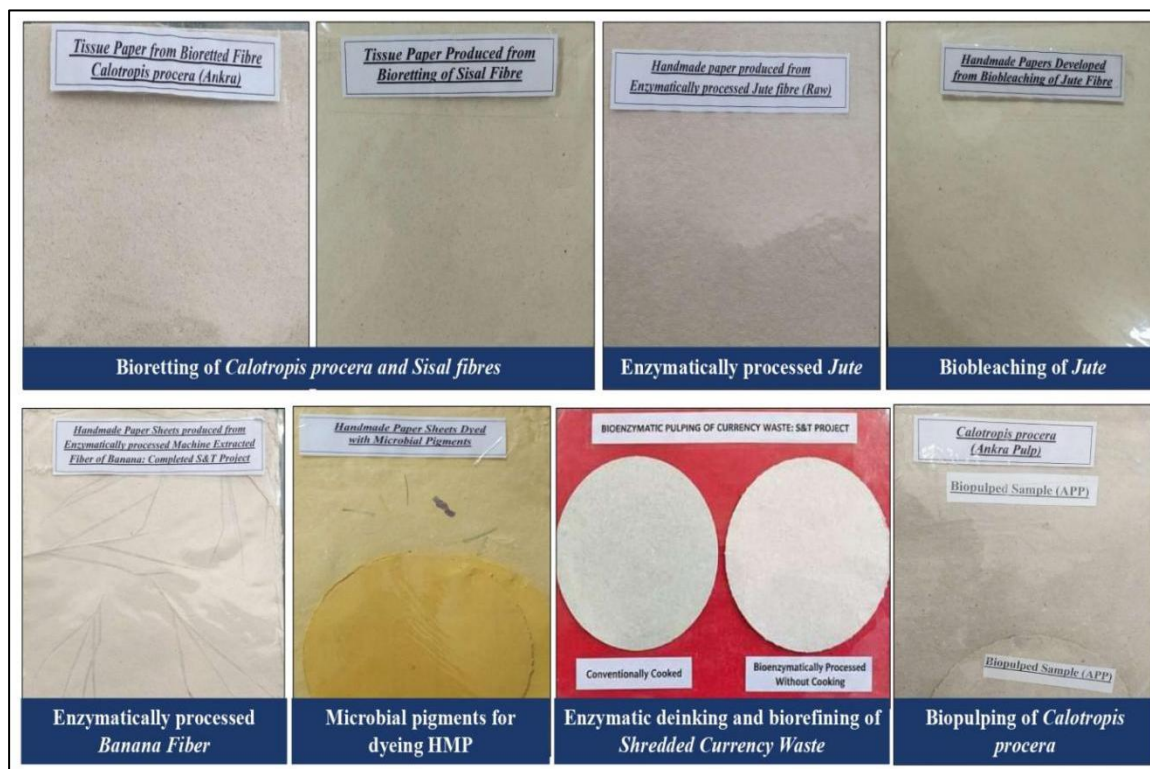


Figure 3 Various handmade paper sheets developed at KNHPI through biotechnology-assisted routes

Conclusion

An integration of biotechnology and circular economy principles may result into sustainable rural handmade paper enterprises. The handmade paper sector is inherently linked with utilization of waste, resource recovery and employment generation. This nature makes it highly suitable for adoption of circular economy principles. The use of various recycled fibres/ waste and non-wood fibre is helpful in sustainable production. However, processing of natural fibres is energy intensive and chemically loaded process. To overcome these problems, biotechnological methods can be applied. Greater integration of biotechnology, circular economy and appropriate modernization can strengthen rural handmade paper enterprises. Therefore, there should be an emphasis of modernizing the handmade paper sector accordingly so that the nation may not only strive further for becoming a Swatch Bharat but also a Knowledge Guru capable of replicating the things in other countries as well.

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