HARNESSING BAMBOO'S POTENTIAL: BIOENERGY PRODUCTION AND BEYOND

Abstract

Bamboos, which belong to the Bambusoideae subfamily of the Poaceae family, demonstrate a broad geographical range that encompasses tropical, subtropical, and temperate areas worldwide. Bamboos have a notable array of 1,642 species distributed among 88 genera, showcasing their unique attributes such as their distinct woody composition, branching arrangements, and internodal segments. The Asia-Pacific area is home to the main hubs of bamboo variety, with South America and Africa following suit. Bamboo, widely acknowledged as "green gold," possesses significant value as a sustainable bioresource, making a substantial contribution to a market valued at $68.8 billion. Advancements in tissue culture technologies have been driven by the challenges encountered in bamboo growth. The field of genetic study has undertaken investigations into exogenous gene expression, despite the challenges posed by the existence of woody features, which can hinder transformation endeavours. The bioenergy production potential of bamboo is remarkable, owing to its quick growth, extensive dispersion, and lignocellulosic composition. Efficient management solutions aim to achieve a harmonious equilibrium between the ecological relevance and economic potential of bamboo.

Keywords: Bamboo; Micropropagation; Genetic Engineering; Bioprocessing; Bio-fuel

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I. INTRODUCTION

Bamboos, which are members of the Poaceae family and more especially the Bambusoideae subfamily, exhibit a wide distribution throughout various tropical, subtropical, and temperate climates worldwide. The total number of genera and species within this group is 88 and 1,642, respectively[1]. Bamboos have distinctive characteristics, including internodes, many branches, and a woody morphology, which distinguish them from other members of the Poaceae family[2]. The Asia-Pacific region is recognised as the primary hub of bamboo variety, exhibiting the greatest number of species, followed by South America. Additionally, certain bamboo species can also be found in Africa[3,4]. Bamboo covers an estimated area of 6.01 million hectares in China, with a diverse range of 43 taxa and 861 species [5,6]. In contrast, India possesses a bamboo coverage of over 16.0 million hectares, with a growth of 3,229 hectares over the course of the past two years.

Bamboo has been highly regarded as a multifunctional and sustainable bioresource, being utilised in various traditional and commercial contexts owing to its exceptional biological characteristics and growth patterns. The International Network for Bamboo and Rattan (INBAR) reported that the anticipated value of the global market for bamboo and rattan products in 2018 was US$68.8 billion. It is anticipated that this particular market would experience a compound annual growth rate of 5.0% over the time frame of 2019 to 2025. An estimated 2.5 billion individuals depend on bamboo as a significant source of economic sustenance [7,8]. This has led to the coining of the popular moniker "green gold"[9]. Nevertheless, the increased demand for bamboo, namely in the pulp and paper sector, has resulted in the over exploitation and subsequent deterioration of wild bamboo populations [10].

The conventional techniques for bamboo propagation encompass the utilisation of seeds, cuttings, and culm cuttings. Nevertheless, the efficacy of these approaches is hindered by the prolonged flowering period of bamboo, which can last for as long as 120 years, as well as the limited seed production and viability, and the predation of seeds by mice and birds [11]. Furthermore, the constrained accessibility of propagation material, its unwieldiness during transportation over long distances, reduced ability to develop roots, and diminished rates of survival pose obstacles to the propagation process through vegetative means [12]. The aforementioned constraints have spurred advancements in the field of reforestation, namely in the realm of tissue culture methodologies. These techniques, particularly beneficial for extensive production efforts, have been designed to enhance the accessibility of resources for breeding initiatives and the preservation of genetic material.

The field of modern biotechnology has made substantial contributions to the study of bamboo, particularly by effectively incorporating and expressing exogenous genes within bamboo plant species. Nevertheless, the implementation of genetic manipulation initiatives in monocotyledonous plants, such as bamboo, may face obstacles arising from the incompatibility between donor and host species. The utilisation of advanced next-generation sequencing technologies has provided researchers with the capability to extensively explore the genome of bamboo. Multiple methodologies, such as mathematical modelling, genomics, proteomics, and transcriptome profiling, are commonly utilised in the investigation of fundamental biological processes across diverse bamboo species [13–17].

The overconsumption of conventional fossil fuels has been a significant factor in the exacerbation of climate change and the degradation of the environment. Consequently, there exists an urgent imperative to cultivate renewable and environmentally conscious energy alternatives as substitutes for fossil fuels, thereby guaranteeing a sustainable and uncontaminated energy provision. A potential answer is the utilisation of lignocellulosic biomass obtained from wood, which has the capacity to function as an energy source that is both sustainable and carbon-neutral.

Bamboo is a notable biomass resource that distinguishes itself by its expeditious development rate, economic feasibility, and capacity for long-term viability[18]. There has been a notable rise in global renewable energy production, with the percentage growing from 23.2% in 2018 to 29% in 2020[19]. Bamboo exhibits a wide distribution over diverse latitudes, particularly spanning the range of 40° north to south. Notably, China, Brazil, and India jointly harbour a significant proportion, accounting for around 60%, of the global bamboo forests [20]. A number of nations in Southeast Asia, Africa, and South America are currently engaged in the preservation and advancement of their bamboo resources, driven by an awareness of its strategic significance [21–23]. China is home to a diverse range of bamboo species, with over 500 varieties identified. Among them, Moso bamboo is the most prevalent, occupying approximately 72.96% of the country's total bamboo-covered land [24].

Bamboo, which exhibits robust growth in tropical and subtropical locations, is a highly prevalent botanical species that fulfils both ornamental and indispensable ecological roles within forest ecosystems [25]. The entity in question serves as a notable carbon sink, effectively sequestering carbon dioxide while concurrently emitting a greater quantity of oxygen, around 30% more, compared to an equivalent amount of wood biomass. Nevertheless, the proliferation of bamboo forests may result in a reduction in the diversity of species and pose a possible threat to the integrity of pre-existing forest ecosystems [26,27]. In order to address this issue, the implementation of short-term rotation harvesting in bamboo forests is suggested as a potential solution, which aims to achieve a harmonious equilibrium between ecological stability and the extraction of bamboo for economic gain [28,29].

The primary constituent of bamboo is lignocellulosic material, which makes up more than 70% of its composition. This characteristic is observed consistently across many species of bamboo [30]. One example of a plant species with a high lignocellulose content is Moso bamboo. Moso bamboo can contain up to 78% lignocellulose, making it a valuable source of lignocellulosic biomass[31]. Several different methods have been identified in recent studies for converting bamboo into energy. These methods include acid-base pretreatment [32,33], biodegradation [34,35], and steam explosion [36]. The aforementioned process has the potential to generate several products, including alcohol [37,38], biogas [39], glucose [34], and bio-oil [40]. The influence of pyrolysis parameters on the behaviour and products of the pyrolysis process in various biomass components has been extensively investigated[41,42].

In recent times, there has been a growing interest in the utilisation of bamboo biomass as a viable substitute for wood and charcoal in many industrial sectors [43]. Despite the considerable body of literature regarding the potential of bamboo for the production of biofuels, there seems to be a dearth of comprehensive research that consolidates and presents the energy potential of various bamboo species. Furthermore, it is worth noting that there is a conspicuous lack of comparative research conducted on diverse technologies and the impact of different bamboo species on the generation of bioenergy. The objective of this chapter is to

compile data regarding the biochemical makeup of specific bamboo species, delineate the potential avenues for utilising bamboo, and emphasise the merits of bamboo as an environmentally sustainable source material for bioenergy. The objective of this study is to provide a comprehensive overview of the numerous bioenergy types that can be derived from bamboo through different conversion techniques. Additionally, this research intends to evaluate an assessment system designed specifically for bamboo species used in energy production.

II. MICROPROPAGATION OF DIFFERENT BAMBOO SPECIES

Micropropagation is an innovative method that enables rapid vegetative proliferation of plants that are typically difficult to replicate. The utilisation of a controlled In vitro environment renders it a more advantageous option to traditional propagation methods. The extensive corpus of research pertaining to the micropropagation of bamboo highlights its considerable importance. Extensive study has been conducted on the In vitro propagation of bamboo species, as indicated by a substantial number of scientific papers. The purpose of this overview is to summarise the advancements achieved in the field of micropropagation techniques specifically designed for various species of bamboo. The initial research on bamboo micropropagation was conducted by Alexander and Rao in the year 1968[44]. A procedure was successfully developed for the micropropagation of Dendrocalamus strictus, employing zygotic embryos as explants during the juvenile stage.

1. **Explant Selection:** The selection of explant and its sterilising are crucial first stages in micropropagation, significantly influencing the outcome of the protocol. In the field of bamboo micropropagation, both juvenile and mature explants are employed, with a preference for the latter[45].The process of shoot emergence from axillary buds is regulated by multiple factors, including as the genotype of the bamboo, its physiological condition, and the timing of explant extraction. Several studies have examined these issues[46–49]. It was revealed that the quantity of axillary shoot buds in Dendrocalamus longispathus was influenced by factors such as the age, time, and position of the explant on the branch[50]. The most promising outcomes were observed when cultures were established utilising young lateral buds, particularly those obtained from the central region of young lateral branches, during the monsoon season in India, which spans from July to September. During this time period, there was also a notable increase in the availability of various explants, as well as a heightened frequency of bud break.

   Certain nodes inside Bambusa nutans, specifically the 5th to 7th nodes, shown a notable capacity for regeneration[51]. The regeneration capability of Arundinaria callosa was found to be greatly influenced by the placement of the nodal axillary bud. Buds located at the distal regions of branches exhibited a lower level of responsiveness in comparison to buds situated at the basal end or middle nodes[52].

   Seasonal fluctuations also have a significant impact. For example, it was shown that Dendrocalamus asper explants obtained during the spring season (February to April) had a higher rate of regeneration compared to explants collected during other seasons. In contrast another report found that the period from April to June, which corresponds to the early summer months, was considered to be the most favourable for Dendrocalamus hamiltonii [48]. This time frame resulted in decreased contamination, efficient shoot start, and a greater rate of bud break.

The precise timing of explant collection is of utmost importance as it significantly affects contamination rates, frequency of bud break, emergence of shoots, and overall plant growth. These differences could potentially be ascribed to fluctuations in the plant's physiological status or alterations in environmental conditions over the course of the year. The correlation between seasonal variations and the ability to regenerate can be attributed to endogenous hormone fluctuations. As an example, the increase in auxin concentrations in the apical meristems during the spring season, attributed to prolonged daylight duration and intensified light intensity, stimulates cellular proliferation and elongation[53,54].

Determining the most favourable periods for tissue collection and beginning of culture holds immense value. These observations provide a foundation for developing efficient techniques for conservation and propagation, which are crucial for safeguarding the genetic diversity of bamboo and mitigating the risk of losing these invaluable species.

2. **Choice of Basal Medium:** The nutritional requirements for tissue culture conducted In vitro, which includes both micro- and macronutrients, exhibit considerable variation. It is worth noting that different species of bamboo have specific demands for their ideal nutrient media, as emphasised by Chang and Ho's research in 1997[55].

The Murashige and Skoog medium (MS) [56]is widely recognised as the predominant foundational medium for the In vitro organogenesis of bamboo. Several basal nutrient media were assessed, including MS, B5 [57],Schenk and Hildebrandt medium (SH)[58], and Woody Plant medium (WPM)[59][60]. The results of the study indicated that a modified MS medium was found to be highly favourable for regeneration, particularly for Bambusa bambos nodes, but WPM exhibited lower effectiveness in this regard.

Other studies evaluated the effects of four basal mediaon Dendrocalamus hamiltoniiand Dendrocalamus asper: Murashige and Skoog (MS), Gamborg's B5, Schenk and Hildebrandt (SH), and Nitsch and Nitsch medium (NN)[61][48,62]. The findings of their study provided further evidence supporting the enhanced regenerative properties of MS. The impact of salt content on axillary bud breakage and regeneration in MS has also been documented. The utilisation of a half-strength Murashige and Skoog (½ MS) medium yielded superior results compared to the full-strength medium for species such as Dendrocalamus strictus and Phyllostachys meyeri[63,64].

The effectiveness of six different media formulations was investigated in inducing callus from zygotic embryos in Dendrocalamusasper[65]. These media included MS, ½ MS, B5, NB (a combination of N6 nutrients and B5 vitamins [66]), HB medium [67], and N6 medium [68]. The results of their study provided further support for the prevailing superiority of MS as the optimal basal medium for the development of callus.The majority of research studies have consistently demonstrated that semisolid basal media exhibit greater efficacy compared to solid media. However, there have been reported cases where liquid media have shown to be more advantageous for shoot induction and proliferation[50,64,69–71].

In conclusion, the MS medium has become a crucial nutritional media for the In vitro propagation of numerous plant species, including bamboo. The nutrient profile

provided by this product is both consistent and versatile, hence promoting the growth and development of resilient plants.

3. **Effect of Plant Growth Regulators and Other Additives:** Carbohydrates, particularly sucrose, play a crucial role in the process of In vitro growth, serving as the principal source of carbon and energy. Plant tissues substantially depend on the culture medium for carbon due to the restricted availability of CO2 in closed culture containers and reduced light intensity [72]. Sucrose, a type of sugar that does not undergo reduction reactions, is commonly used in bamboo tissue cultures. This preference is attributed to its ability to resist enzymatic breakdown, its involvement in maintaining the osmotic balance of the culture media, and its contribution to the initiation of shoot and root growth [73,74]. Bambusatudla is capable of thriving at a sucrose concentration of 2%, which deviates from the commonly accepted benchmark of 3%[75]. Nevertheless, the ideal concentration differs among species and is affected by several parameters such as environment, dietary requirements, and the stage of tissue growth [76,77]. It is worth noting that Bambusa vulgaris demonstrated enhanced growth in media without sucrose[78]. In the context of In vitro bamboo propagation, sucrose plays a crucial role by aiding many physiological processes such as energy provision, regulation of water potential, and promotion of shoot and root formation [74,79].

4. **Caulogenesis:** Plant growth regulators (PGRs) play a crucial role in facilitating successful In vitro propagation. The need is determined by various parameters, including genotype, tissue stage, explant type, and culture environment [80]. Cytokinins, specifically 6-benzylaminopurine (BAP), have been found to exert a significant impact on the process of axillary bud formation in bamboo [81–83]. Although BAP is the prevailing cytokinin, the efficacy of other cytokinins such as kinetin (Kn) and 2-isopentenyl adenine (2-iP) has been comparatively lower. Nevertheless, the synergistic use of auxins and cytokinins, specifically BAP and 1-naphthaleneacetic acid (NAA), has demonstrated advantageous outcomes in the process of shoot induction [84,85]. Thidiazuron (TDZ) has demonstrated efficacy in promoting direct organogenesis in specific species[63,86].

   In order to mitigate explant browning, various antioxidants such as adenine sulphate (AdS), activated charcoal, and amino acids are employed. The use of AdS has demonstrated efficacy in facilitating robust shoot multiplication[87]. Additional antioxidants, including as ascorbic acid, citric acid, and cysteine, have demonstrated potential in augmenting shoot output [60,62,88].

5. **Rhizogenesis:** The process of establishing roots in bamboo shoots cultivated In vitro is crucial for achieving good micropropagation. The nutritional composition, particularly the presence of auxins, has a substantial impact on facilitating robust root growth. Nevertheless, previous research has indicated that certain bamboo species, such as Pleioblastus pygmaeus, have demonstrated successful root development in a media devoid of auxin [89,90]. Multiple studies consistently observe that 1/2 MS is an appropriate growth medium for bamboo rooting, exhibiting greater efficacy compared to full-strength MS.

   Auxins, specifically Indole-3-butyric acid (IBA), have been recognised as essential factors for the process of root formation in bamboo shoots that are cultivated In

vitro. Indole-3-butyric acid (IBA), either in isolation or in conjunction with naphthaleneacetic acid (NAA), is widely employed as the predominant auxin for this particular objective. As an example, it was shown that Bambusaglaucescens demonstrated a rooting response of 100% when cultured on a Murashige and Skoog (MS) medium supplemented with 25 µM indole-3-butyric acid (IBA) [91]. It was observed that Dendrocalamusasper exhibited a rooting success rate of 90% when treated with 2 mg/L IBA in 1/2 MS medium[65]. Certain research utilised mixtures of auxins, and in certain cases, cytokinins were also included. As an example, on employing a mixture of 0.44 µM BA, a type of cytokinin, and 4.90 µM IBA achieved the most favourable results in terms of root development in Pseudoxytenantherastocksii shoots[92].

The significance of coumarin in promoting root development in bamboo shoots has been emphasised in many species, such as Bambusatuldaand Dendrocalamus giganteus[75,93]. The phenomenon of ex vitro root induction, which involves the rooting of shoots outside the confines of the culture media, has been the subject of investigation as well. An example of this may be seen in a study where Pseudoxytenantherastocksii stems were subjected to a 10-minute treatment with NAA, resulting in a 99% success rate of ex vitro rooting[94].

The potential advantages of the 1/2 MS medium's diminished levels of micronutrients and macronutrients may contribute to enhanced rooting capabilities. Root systems generally require greater quantities of certain nutrients, such as phosphorus and potassium, in comparison to aboveground plant structures. The restriction of these nutrients has the potential to impede shoot development while promoting root growth[95]. The regulation of root development is a complex process that involves the coordinated action of various plant growth regulators (PGRs), including auxins and cytokinins. Auxins in the nutritional medium have been found to especially facilitate the process of root growth. Nevertheless, the optimal medium composition may vary depending on the specific bamboo species and tissue type, hence requiring a customised methodology for each individual species.

Table 1: Plant Regeneration and Propagation Protocols for Various Bamboo Species

Species	Caulogenesis			Rhizogenesis			References
	Explant	Treatment	Shooting	Treatment	Rooting (Number, lenght)	Plant Survival	
Bambusa arundinacea	Seeds	Murashige & Skoog + (4.50–44.5 µM) 6-Benzylaminopurine	Multiple shoots	1/2 Murashige & Skoog + (4.90 µM) Indole-3-butyric acid	Rooting Observed	N/A	[81]
Bambusa arundinacea	Nodes	Murashige & Skoog + (13.32 µM) 6-Benzylaminopurine + (2.50 µM)Indole-3-butyric acidMurashige & Skoog + (13.32 µM) 6-Benzylaminopurine + (2.46 µM) Indole-3-butyric acid + (4.00%) Coconut Water	24.2	Murashige & Skoog + (14.80 µM) Indole-3-butyric acid + (11.80 µM) $AgNO_3$	9.34, 7.40 cm	85.00	[96]
Bambusa balcooa and Bambusa bambos	Nodes	Murashige & Skoog (Liquid) + additives (AA 283.90 µM) + (1	3–8	Murashige & Skoog + (4.90 – 9.80 µM/5.40 – 10.80 µM) 1-Naphthaleneace	2.00–3.00	> 90.00	[71]

		30.20 µM) Citric Acid + (206.4 µM) Cysteine +(0.50 -1.35 µM) 1-Naphthaleneacetic Acid + (4.50 – 11.0 µM) 6-Benzylaminopurine		tic Acid/Indole-3-butyric acid			
Bambusa bambos	Embryonic axis derived fromcaryopsis	Murashige & Skoog + (5.0 µM) 6-Benzylaminopurine Murashige & Skoog + (2.5 µM) 6-Benzylaminopurine	Multiple shoots	Murashige & Skoog + (2.5 µ M) 6-Benzylaminopurine + (0.1 µM) GA_3 + (50.0µM) 1-Naphthaleneacetic Acid	4.00–20.00	80–85	[97]
Bambusa nutans	Seeds	Murashige & Skoog Murashige & Skoog + (2.30 µ M) 6-Benzylaminopurine	Multiple shoots	Murashige & Skoog + (2.30 µ M) 6-Benzylaminopurine	Rooting Observed	N/A	[98]
Bambusa oldhamii	Meristems	Murashige & Skoog + (0.45 µ M) Thidiazuron	Multiple shoots	Murashige & Skoog + (10.74 µM or	3.39–4.28, 7.19–7.75 cm	83.00	[86]

				26.85 µM) 1-Naphthaleneacetic Acid			
Bambusa tudla	Seeds	Murashige & Skoog basal Murashige & Skoog + 6-Benzylaminopurine(8.00 µM) + Kinetin(4.00 µM)	Multiple shoots	Murashige & Skoog + (1.00 µM) Indole-3-acetic acid + (4.00 µM) Coumarin	4.0	80.00	[75]
Dendrocalamus asper and Dendrocalamus strictus	Nodes	Murashige & Skoog (Liquid) + (283.90 µM) Ascorbic Acid + (130.20 µM) Citric Acid + (206.40 µM) Cysteine +(1.40 µM) 1-Naphthaleneacetic Acid + (1.20 µM) Thidiazuron	3.00 –8.00 shoots	Murashige & Skoog +(4.90 – 9.80 µM/5.40 – 10.70 µM) Indole-3-butyric acid/1-Naphthaleneacetic Acid	Rooting Observed	N/A	[71]
Dendrocalamus asper	Zygotic embryos	Murashige & Skoog + (13.60 µM or 2.30 µM) 2,4-D (Callus Induction)	Multiple shoots	½ Murashige & Skoog + (14.80 µM) Indole-3-butyric acid	6.00, 3.40 cm	95	[65]

		Murashige & Skoog +(13.40 µ M) 6-Benzylaminopuri ne + (2.70 µM) 1 - Naphthaleneaceti c Acid					
Dendrocalamushamilt onii	Nodes	Murashige & Skoog basal Murashige & Skoog + (8.00 µ M) 6-Benzylaminopuri ne + (1.00 µM) 1-Naphthaleneaceti c Acid	3.00 –5.00 shoots	Murashige & Skoog+ (100 µM) Indole-3-butyric acid	> 6.00 50.00 mm	> 90.00	[99]
Dendrocalamushamilt onii	Nodes	½ Murashige & Skoog ½ Murashige & Skoog or Murashige & Skoog liquid + (11.00 µ M) 6-Benzylaminopuri ne	4–6 shoots	½ Murashige & Skoog + Activat ed Charcoal (0.30%, w/v) or Choline Chloride (21.50 – 64.5 µM) + (2.5 µM)Indole-3-butyric acid or (0.50/0.60 µM) Indole-3-acetic acid/1-	Rooting Observed	80.00 – 85.00	[100]

				Naphthaleneacetic Acid			
Oxytenanthera abyssinica	Nodes	Murashige & Skoog + (22.20 µM) 6-Benzylaminopurine + (1.00 µM) 1-Naphthaleneacetic Acid	4.40, 7.60 cm	Murashige & Skoog + (39.40 µM) Indole-3-butyric acid	1.40	70.00	[84]
	Seeds	Murashige & Skoog + (17.80 µM) 6-Benzylaminopurine	4.80, 4.50 cm	½ Murashige & Skoog + (39.40 µM) Indole-3-butyric acid	9.42, 4.20 cm	91.67	[101]
Phyllostachys meyeri	Nodes	SDW + 0.10% PPM™ Modified liquid ½ Murashige & Skoog	Multiple shoots	½ Murashige & Skoog (Liquid) (Modified)	29.70 (rooting %)	N/A	[64]
Thamnocalamus spathiflorus	Nodes	Murashige & Skoog basal Murashige & Skoog + (5.00 µM) 6-Benzylaminopurine + (1.00 µM) Indole-3-butyric acid	28.6, 33.7 cm	½ Murashige & Skoog + (150.00 µM) Indole-3-butyric acid	10.60, 31.40 cm	100.00	[102]

Bambusa balcooa	Nodes	Murashige & Skoog + (4.40 µ M) 6-Benzylaminopuri ne + (2.32 µM) Kinetin Murashige & Skoog (Liquid) + (6.60 µM) 6-Benzylaminopuri ne + (2.32 µM) Kinetin + 2.50% (v/v) Coconut Water + (555.00 µM) myo-inositol	5–8, 3.59 cm	½ Murashige & Skoog + (5.71 µ M) Indole-3-acetic acid + (4.90 µM) Indole-3-butyric acid + (5.37 µM) 1-Naphthaleneace tic Acid	87.50 (rooting %)	88.00	[103]
	Nodes	Murashige & Skoog + (4.44 µ M) 6-Benzylaminopuri ne	8–10, 3.10 cm	Murashige & Skoog + (4.44 µ M) 6-Benzylaminopu rine + (16.02 µ M) 1-Naphthaleneace tic Acid	2.10, 1.50 cm	75.00	[104]
	Nodes	Murashige & Skoog (Liquid) + (11.25 µM) 6-Benzylaminopuri ne + (4.50 µM)	3.00 –4.00	½ Murashige & Skoog + (1.00 µ M) Indole-3-butyric acid	2.00 –3.00	N/A	[105]

		Kinetin					
	Nodes	Murashige & Skoog + (22.20 µ M) 6-Benzylaminopurine Murashige & Skoog + (13.40 µ M) 6-Benzylaminopurine	12.67, 2.90 cm	Murashige & Skoog + (24.20 µM) 1-Naphthaleneacetic Acid	236.00, 13.00 cm	90.00	[106]
Bambusa balcooa, Bambusa nutans, Bambusa salarkhanii, Bambusa vulgaris	Nodes	Murashige & Skoog (Liquid) + (4.44–22.20 µM) 6-Benzylaminopurine	3.00 –30.00, 3.00 –5.00 cm	½ Murashige & Skoog + (5.40 – 16.20 µM) 1-Naphthaleneacetic Acid + (5.00–24.6 µM) Indole-3-butyric acid	Rooting Observed	80.00	[107]
Bambusa bamboos	Nodes	Murashige & Skoog (Liquid) + (8.90 µM) 6-Benzylaminopurine + (4.60 µM) Thidiazuron	3.14, 3.43 cm	½ Murashige & Skoog + (2.50 mg/l) Indole-3-butyric acid + (2.50 mg/l) 1-Naphthaleneacetic Acid	8.72, 9.13 cm	100.00	[70]
Bambusa glaucescens	Nodes	Murashige & Skoog + (5.00 µ	3.58, 3.45 cm	Murashige & Skoog + (25.0 µ	9.67, 1.08 cm	100.00	[91]

		M) 6-Benzylaminopurine + (15.00 µM) Kinetin		M) Indole-3-butyric acid			
Bambusa nutans	Nodes	Murashige & Skoog + (2.20 µM) 6-Benzylaminopurine	Multiple shoots	Murashige & Skoog + (49.00 µM) Indole-3-butyric acid	4.90, 1.30 cm	90.00	[108]
Bambusa tudla	Nodes	Murashige & Skoog (Liquid) + (10.00 µM) 6-Benzylaminopurine + (0.10 µM) Indole-3-acetic acid Murashige & Skoog (Liquid) + (12.00 µM) 6-Benzylaminopurine + (100.00 µM) glutamine + (0.10 µM) Indole-3-acetic acid	Multiple shoots	Murashige & Skoog (Liquid) + (40.00 µM) coumarin	3.10, 6.70 cm	98.30	[109]
Bambusa tudla	Nodes	Murashige & Skoog + (13.30 µM) 6-Benzylaminopuri	Multiple shoot	½ Murashige & Skoog + (14.70 µM) Indole-3-butyric acid	86.67 %	81.81	[110]

		ne Murashige & Skoog + (8.80 µM) 6-Benzylaminopurine + (13.90 µM) Kinetin		+ (68.40 µM) Coumarin			
Bambusa vulgaris	Nodes	Murashige & Skoog + (17.76 µM) 6-Benzylaminopurine	26.00, 5.70 cm	Murashige & Skoog + (14.76 µM) Indole-3-butyric acid	40.00%	100.00	[111]
Bambusa wamin	Nodes	Murashige & Skoog + (22.20 µM) 6-Benzylaminopurine Murashige & Skoog + (2.00 mg/l) 6-Benzylaminopurine + (0.80 mg/l) Kinetin	12.90, 3.72 cm	Murashige & Skoog + (7.50 mg/l) Indole-3-butyric acid	95.83, 5.26, 1.48 cm	80.00 – 90.00	[82]
Dendrocalamus asper	Nodes	Murashige & Skoog + (66.60 µM) 6-Benzylaminopurine Murashige & Skoog + (8.88 µ	14.00, 6.77 cm	Murashige & Skoog + (24.10 µM) Indole-3-butyric acid	93.33%, 7.33, 6.43 cm	85.00	[112]

		M) 6-Benzylaminopurine + (171.50 µM) Adenine Sulphate					
Dendrocalamus asper	Nodes	Murashige & Skoog + (15.00 µM) 6-Benzylaminopurine Murashige & Skoog + (10.00 µM) 6-Benzylaminopurine + (75.00 µM) Adenine Sulphate	27.60, 3.20 cm	½ Murashige & Skoog + (5.00 µM) Indole-3-butyric acid + (5.00 µM) 1-Naphthaleneacetic Acid	10.00, 1.23 cm	100.00	[62]
Dendrocalamus hamiltonii	Nodes	Murashige & Skoog basal Murashige & Skoog + (8.00 µM) 6-Benzylaminopurine + (1.00 µM) 1-Naphthaleneacetic Acid	3–5, 1.53 cm	Murashige & Skoog + (100.00 µM) Indole-3-butyric acid	> 6.00, 5.00 cm	70.00	[99]
Dendrocalamus hamiltonii	Nodes	Murashige & Skoog + (1.50 µ	30.90, 2.10 cm	Murashige & Skoog + (25.00	12.200, 2.00 cm	85.00	[48]

		M) Thidiazuron Murashige & Skoog + (56.00 µM) Ascorbic Acid		µM) Indole-3-butyric acid + (36.00 µM) Choline Chloride			
Dendrocalamushamiltonii	Nodes	Murashige & Skoog + (4.60 µM) 6-Benzylaminopurine	14.70, 4.30 cm	Murashige & Skoog + (1.00 mg/l) Indole-3-acetic acid + (1.00 mg/l) Indole-3-butyric acid + (1.00 mg/l) 1-Naphthaleneacetic Acid	11.100	N/A	[113]
Dendrocalamus longispathus	Nodes	Murashige & Skoog + (4.40 µM) 6-Benzylaminopurine + (4.60 µM) Kinetin	6–8, 2–5 cm	Murashige & Skoog + (4.40 µM) 6-Benzylaminopurine + (4.60 µM) Kinetin	Rooting Observed	90.00	[114]
Drepanostachyum falcutum	Nodes	Murashige & Skoog + (24.40 µM) 6-Benzylaminopurine or (25.50 µM) Kinetin Murashige & Skoog + (15.54 µ	37.80, 2.20 cm	Murashige & Skoog + (31.90 µM) Indole-3-butyric acid	11.30, 2.18 cm	90.00 – 95.00	[115]

		M) 6-Benzylaminopurine					
Guadua angustifolia	Nodes	Murashige & Skoog + (3.00 mg/l)6-Benzylaminopurine + (2.00 mg/l) PPM™	5.00 –10.00, 15.00 – 20.00 cm	Murashige & Skoog + (3.00 mg/l) 6-Benzylaminopurine + (2.00 mg/l) PPM™	10.00 – 15.00	100.00	[116]
Melocanna baccifera	Nodes	Murashige & Skoog + (13.30 µM) 6-Benzylaminopurine Murashige & Skoog + (13.30 µM) 6-Benzylaminopurine +(9.20 µM) Kinetin	18.170	½ Murashige & Skoog + (3.00 mg/l) Indole-3-butyric acid + (103.0 mg/l) coumarin	81.67 (rooting %)	70.3	[110]
Melocanna baccifera	Nodes	Murashige & Skoog + 6-Benzylaminopurine 20.0 µM Murashige & Skoog + 6-Benzylaminopurine 15.0 µM + Kineti	Multiple shoots	½ Murashige & Skoog + (25.0 µM) Indole-3-butyric acid	Rooting Observed	N/A	[117]

		n 3.0 µM					
Pseudoxytentanthera stocksii	Nodes	Murashige & Skoog + (26.6 µ M)6-Benzylaminopuri ne Murashige & Skoog + (17.6 µ M)6-Benzylaminopuri ne + (1.3 µM) 1-Naphthaleneaceti c Acid	41.9, 8.13 cm	½ Murashige & Skoog + (4.90 µ M) Indole-3-butyric acid	24.30, 12.00 cm	96.00	[88]
Pseudoxytentanthera stocksii	Nodes	Murashige & Skoog + (2.21 µ M)6-Benzylaminopuri ne + (2.68 µM) 1-Naphthaleneaceti c Acid + (283.93 µ M) ascorbic acid + (118.10 µ M) Citric Acid + (104.04 µ M) Cysteine + (342. 24 µM) Glutamine	4.0, 3.56 cm	½ Murashige & Skoog + (4.90 µ M) Indole-3-butyric acid + (0.44 µM) 6-Benzylaminopu rine + (283.93 µM) as corbic acid + (118.10 µ M) Citric Acid + (104.04 µM) Cysteine + (342. 24 µM) glutamine	5.30, 3.64 cm	80.00	[92]

Pseudoxytentanthera stocksii	Nodes	Murashige & Skoog + (1.34 µ M) 1-Naphthaleneaceti c Acid+ (179.00 µM) Choline Chloride + (283. 80 µM) Ascorbic Acid + (206.30 µ M) Cystein	Multiple shoots	Murashige & Skoog + (5.37 µ M) 1-Naphthaleneace tic Acid	Rooting Observed	N/A	[94]
Thamnocalamus spathiflorus	Nodes	Murashige & Skoog + (5.00 µ M) 6-Benzylaminopuri ne + (1.00 µM) Indole-3-butyric acid	28.60, 33.70 cm	½ Murashige & Skoog + (150.0 0 µM) Indole-3-butyric acid	10.60, 31.40 cm	100.00	[102]
Thyrsostachys oliveri	Nodes	Murashige & Skoog + (4.40– 22.00 µM) 6-Benzylaminopuri ne	3.00 –21.00, 0.50 –4.00 cm	½ Murashige & Skoog + (5.40 – 16.20 µM) 1-Naphthaleneace tic Acid +(4.90 – 24.50 µM) Indo le-3-butyric acid	Rooting Observed	100.00	[107]

6. **Somatic Embryogenesis:** Somatic embryogenesis is a phenomenon characterised by the conversion of non-reproductive plant cells into pluripotent embryonic stem cells, which subsequently undergo differentiation to form a somatic embryo when exposed to appropriate environmental cues. This methodology presents a cost-efficient approach to the large-scale production of bamboo species that have historically posed challenges in terms of propagation.

   The pioneering research on the process of bamboo somatic embryogenesis was carried out by Mehta et al. (1982) specifically focusing on Bambusaarundinacea [118]. Subsequent studies were able to achieve effective germination and maturation of somatic embryos in three distinct bamboo species by the utilisation of a specialised nutritional medium[76]. Another study, a methodology was developed for Phyllostachys edulis in which viable somatic embryos were successfully generated from embryogenic callus obtained from zygotic embryos[119]. These somatic embryos subsequently underwent maturation and developed into plantlets. Previous studies have documented the identification of ideal growth conditions for the initiation of somatic embryogenesis in many bamboo species, including Bambusa oldhamii, Bambusa beecheyana, and Sinocalamus latifolia[120,121]. A studyemployed TDZ, a distinct growth regulator, to induce germination of somatic embryos in Bambusaedulis[122].

   A distinctive investigation showcased the regeneration of plantlets of Dendrocalamusstrictus capable of tolerating sodium chloride[123]. This was achieved through the utilisation of salt-tolerant embryogenic callus and the process of somatic embryogenesis. The experimental procedure entailed subjecting the callus to progressively higher concentrations of NaCl, followed by inducing its differentiation into somatic embryos under carefully controlled conditions. In their study, Gillis et al. (2007) successfully attained a conversion rate of 46% for the transformation of somatic embryos into plantlets in Bambusabalcooa. This was accomplished through the induction of embryogenic callus from pseudo-spikelets, followed by subsequent cultivation on a regeneration medium[124].

7. **In Vitro Flowering in Various Bamboo Species:** Bamboo species have distinct reproductive patterns. These organisms are distinguished by their monocarpic nature, exhibiting a prolonged period of vegetative growth that can last for more than a century in specific cases. Following an extended duration, these organisms have a single flowering event and generally experience mortality subsequent to flowering [125,126]. The intricate and protracted flowering cycle poses challenges to conventional breeding endeavours.

   The utilisation of in vitro flowering presents a promising prospect, since it enables the regulation and acceleration of the flowering process inside a regulated and aseptic setting [127]. The frontier of bamboo research delved into in 1990, with the success fulin vitro induction of bamboo flowering and subsequent seed production [128].

   Cytokinin, a phytohormone, assumes a crucial function in the stimulation of in vitro blooming in bamboo[129,130]. It is widely acknowledged as a key stimulus for the initiation of the blossoming process [131–133]. Nevertheless, different bamboo species exhibit diverse reactions to cytokinin. For example, a concentration of 53.8 μM Kn was found to be successful in promoting flowering in Phyllostachysedulis, but it did not have the same impact on Bambusaarundinacea [134,135].

Certain kinds of bamboo necessitate a combination of cytokinins and other supplementary substances in order to induce flowering in vitro. As an illustration, it was observed that Bambusaarundinacea exhibited flowering alone in the presence of a medium containing a combination of 0.26 µM zeatin and 4.90 µM 2iP, along with 2.71 µM AdS. However, the presence of cytokinins alone did not induce flowering in this species [134]. On the other hand, Dendrocalamusstrictus exhibited flowering when treated with a mixture of 2.21 µM BA, 1.23 µM IBA, 1.44 µM gibberellic acid, and 2.14 µM AdS, but the application of BA alone did not induce flowering[76]. According to the findings of another inquiry, it was observed that Bambusapervariabilis × Dendrocalamuslatiflorus exhibited flowering when subjected to a medium containing 8.87–17.7 µM BA, 2.32–4.64 µM Kn, and 100 ml/L coconut water at a concentration of ¾ MS. However, Dendrocalamusbrandisii and Dendrocalamusoldhamii did not display the same response under these conditions[136].

Several alternative approaches have been investigated in previous studies, including the manipulation of the medium's pH and the use of various plant growth regulators, acids, and coconut water [130,134,136]. Nevertheless, achieving regular success continues to be difficult to attain.

III. GENETIC ENGINEERING OF BAMBOO

The process of genetic transformation is a highly effective technique utilised to introduce targeted genes into plant organisms, hence facilitating the augmentation of favourable characteristics. Although this approach has been extensively utilised in numerous plant species, its efficacy in woody plants, including bamboo, has been constrained. The primary cause of these difficulties can be attributed to the intrinsic obstacles presented by the woody characteristics of bamboo, including the process of lignification.

Although bamboo poses challenges for genetic transformation, particularly when compared to well-studied herbaceous species such as Arabidopsis thaliana or Zea mays, notable progress has been made in this area in recent years. Several approaches to bamboo genetic transformation have been investigated, encompassing:

1. **Agrobacterium Tumefaciens-Mediated Transformation:** This bacterium is used to transfer genes into plants. Lc gene of maize was introduced to Dendrocalamuslatiflorususing this method [137]. This method has also been employed this method for Dendrocalamusgiganteus and Dendrocalamushamiltonii, respectively[138,139].

2. **Protoplast Fusion:** This involves fusing cells without their cell walls. A transient transformation protocol was established for protoplasts from Phyllostachysedulis and Dendrocalamuslatiflorus, achieving a notable transformation efficiency[140].

3. **Particle Bombardment:** This method uses high-velocity microprojectiles to deliver genes into cells. Phyllostachysnigrawas successfully transformed using this technique[141].

Somatic embryos (SEs) are frequently chosen as the explant of choice for bamboo genetic transformation owing to their inherent capacity for repeated development. For example, attempts have been undertaken to improve bamboo's ability to withstand severe temperatures by the utilisation of transgenic techniques. Bacterial CodA gene was successfully incorporated the CodA gene from bacteria into Dendrocalamuslatifolia, leading to a notable enhancement in the plant's ability to withstand low temperatures[142].Despite these advancements, genetic transformation in bamboo remains a challenging endeavour. Factors contributing to these challenges include:

4. **Lack of Established Protocols:** Bamboo's unique physiology and growth characteristics require specialized protocols for successful transformation.

5. **Low Regenerative Capacity:** Bamboo's ability to regenerate after transformation is often limited, making the establishment of transgenic plants challenging.

6. **Complex Genome:** Bamboo's genome is intricate, which can complicate the process of introducing and expressing foreign genes.

7. **Lack of Transformation Vectors:** Suitable vectors for bamboo transformation are limited.

8. **Limited Research:** Bamboo, being a non-model organism, has received less attention in genetic research compared to other plants.

Table 2: Genetic Transformation Strategies and Targets in Bamboo Species.

Species	Explant used	Method(s) of transformation	Insert	Purpose of transformation	Purported function	References
Dendrocalamus latiflorus	Young shoot and callus from anther	Agrobacteriumtumefaciens	Bacterial CodA gene	Cold stress tolerance	Incorporating CodA into Ma bamboo	[142]
Dendrocalamuslatiflorus	Root	Agrobacteriumtumefaciens (EHA 105)	RUBY reporter	Optimizing the leaf's transformation to increase the overexpression of foreign proteins	GUS expression after leaf infection	[140]
Dendrocalamus latiflorus	Internode	Agrobacterium tumefaciens	PSY1 (Phytoene synthase)	Changes in plant height	Mutants that have prolonged vegetative growth cycles	[143]
Phyllostachys edulis	Root	Agrobacterium tumefaciens (EHA 105)	RUBY reporter	To enhance leaf transformation's ability to overexpress foreign proteins	infection of the leaf, then GUS expression	[140]

Dendrocalamus hamiltonii	Somatic embryo	Agrobacterium tumefaciens (strains GV2260 and GV3101)	The neomycin phosphotransferase (nptII), nopaline synthase (NOS), promoter-nptII-NOS terminator (PolyA), gus reporter gene interrupted by plant introns (gus-int), nptII selective gene under NOS promoter of Agrobacterium, and marker gene -glucuronidase	Minimizing wax buildup, cell wall thickening, and avoiding necrosis brought on by polyphenol at the site of wounds	he process of co-cultivation was conducted on minimal salt medium (MSM) supplemented with benzyladenine (BA) and acetosyringone, a vir gene inducer, following a two-day infection period in the susceptible environment (SE).	[139]
Phyllostachys nigra	Shoots	Particle bombardment	AcGFP1andmCherry	To create a workable, effective transformation technique utilizing bamboo suspension cells.	Both genes were visible in transformed cells produced from bamboo suspension cells.	[141]

IV. BAMBOO AS A MODEL FOR GENOMIC STUDIES

The examination of gene expression offers valuable insights into the activity and functionality of genes within an organism. The underlying biological processes of bamboo remain little understood, despite its widespread use for numerous applications throughout history. Nevertheless, the emergence of advanced next-generation sequencing technology has enabled researchers to explore bamboo's transcriptome profiles in greater detail, providing valuable insights into various crucial biological processes.Molecular methodologies have been employed to investigate the growth, development, and other physiological processes of bamboo:

1. **Rapid Growth:** Bamboo is renowned for its swift growth rate. By analysing the transcriptomic profiles, researchers have identified genes and pathways associated with cell division, elongation, and differentiation that contribute to this rapid growth.

2. **Flowering:** Bamboo's flowering patterns, especially its sporadic mass flowering events, have long been a subject of curiosity. Through gene expression analysis, genes related to flowering time, floral organ development, and hormonal pathways have been identified.

3. **Primary Thickening:** This process is crucial for bamboo's mechanical strength. Genes associated with vascular development, lignin biosynthesis, and cell wall formation have been studied to understand this thickening process better.

4. **Metabolic Processes:** Bamboo's ability to synthesise and break down various compounds is vital for its survival and growth. Transcriptomic studies have highlighted genes involved in photosynthesis, respiration, nutrient uptake, and secondary metabolite production.

5. **Stress Tolerance:** Bamboo species exhibit resilience to various environmental stresses. Gene expression analysis has identified genes related to drought resistance, salinity tolerance, and pathogen resistance.

- **Regulation of Growth, Development, and Responses to Environmental Stresses:** In contrast to numerous monocotyledonous plants, bamboo exhibits distinctive growth patterns, characterised by rapid branch elongation and prolonged intervals between flowering events. As an example, certain species of bamboo, such as Phyllostachysedulis, have the capacity to achieve a growth rate of up to 1 metre in a single night during periods of optimal growth. Passiflora edulis, a non-timber forest species of worldwide importance, possesses considerable ecological value. However, despite the extensive research conducted to identify the specific genes that influence metabolism, growth, and development, the underlying genetic mechanisms responsible for this rapid growth are still not fully understood.

  The publication of the genome sequence of Phyllostachysedulis provides researchers, the opportunity to precisely identify and thoroughly investigate the MADS-box family[144]. The MADS-box genes are responsible for the production of essential transcription factors that regulate several aspects of plant growth and development. The PeMADS gene has been discovered as a crucial factor in the

transition from the vegetative phase to the reproductive phase. Significantly, the induction of early blooming in Arabidopsis was seen through the overexpression of PeMADS5, hence indicating the need for additional investigation.

The bZIP transcription factor family, which is among the largest in plants, is known to have a significant impact on several growth, development, and stress response mechanisms [145]. A study conducted by Pan et al. (2019) provides insights into the significance of bZIP genes in Phyllostachysedulis[146]. The researchers successfully identified a total of 18 PebZIP genes that play crucial roles in several biological processes such as growth, development, stress response, and hormone signalling. In a similar vein, a study emphasised the significance of 16 TCP transcription factors in Phyllostachysedulis, specifically elucidating their involvement in the plant's reaction to environmental stresses and control by hormones[6].

The WRKY transcription factor family, which plays a crucial role in plant development and stress responses, has been the subject of investigation in bamboo as well [147]. A total of 89 PeWRKY genes in the species Phyllostachys edulis[148]. Notably, the PeWRKY83 gene exhibited improved physiological characteristics when introduced into transgenic Arabidopsis plants. Furthermore, the participation of the Aux/IAA and auxin response factor (ARF) gene families in the growth and developmental stages of Phyllostachys eduliswas extensively investigated by [5].

In order to further investigate the phenomenon of accelerated growth in bamboo shoots, a study was conducted that focused on examining the involvement of brassinosteroid (BR) in the developmental process of Phyllostachys edulis shoots[149]. The researchers successfully identified the PSBR1 gene, which exhibits a negative response to BR. In their experimentation with Arabidopsisthaliana, they observed that over expression of this gene resulted in growth inhibition. Furthermore, another investigation identified the genes associated with brassinosteroid (BR) in the context of shoot growth in Phyllostachys edulis[150]. The researchers successfully identified a total of 64 genes that are involved in the processes of BR production and signal transduction.

The NAC transcription factor family, which plays a crucial role in various biological processes such as growth, development, and stress responses, has been the subject of investigation in the context of bamboo as well [147]. The discovery of the PeNAC3 gene, which, when over expressed in Arabidopsis thaliana, resulted in the onset of senescence at an earlier stage and enhanced growth in the presence of stressful environmental conditions.

The growth, development, and stress responses of bamboo are regulated by a complex interplay of genes and transcription factors. Comprehending these complex genetic relationships is crucial for augmenting the resilience and growth of bamboo, under both typical and unfavourable circumstances.

In summary, the growth, development, and stress responses of bamboo are regulated by a complex interplay of genes and transcription factors. Comprehending the complex genetic linkages is crucial in augmenting the resilience and growth of bamboo, under both typical and unfavourable circumstances.

- **Synthesis of Lignin and Cellulose:** The process of lignin synthesis in plants is a complex phenomenon that is closely linked to cellular development and maturation. It is regulated by a diverse array of transcription factors and their associated genes[151,152]. The crucial role of Homeobox (HB) genes in coordinating several aspects of plant growth has been identified[153]. A study investigated the role of 115 HB genes in shoots of Phyllostachys edulis, highlighting their substantial involvement in the biosynthesis of lignin. Moreover, the expression of the HB gene in Phyllostachys edulis is subject to a complex regulatory mechanism, characterised by multiple layers of control. This regulatory system results in the upregulation of HB gene expression in parallel with the growth of shoots.

  Sucrose synthase (SUS) is a pivotal enzyme in the domain of plant sucrose metabolism, playing a critical role in the synthesis of cellulose [154]. A study was conducted that emphasised the significance of SUS genes in the developmental stages of shoots and leaves in Bambusaoldhamii[13]. Four separate SUS genes were found, which are involved in either providing substrates for polysaccharide production or generating the energy required for rapid growth. A separate investigation revealed the expression patterns of seven SUS genes in Bambusaemeiensis[155]. The primary objective of this study was to elucidate the probable functions of these genes in cellulose synthesis and hormone reactions. The results of their study unveiled diverse patterns of gene expression for each BeSUS gene in different tissue types. For example, the activity of BeSUS2 was mostly observed in the roots, whereas BeSUS5 exhibited dominance in the budding shoots. Moreover, the expression of these genes was shown to be significantly increased in response to exposure to ABA and MeJA, indicating their potential role in mediating responses to various environmental stresses.

  Subsequent research endeavours ought to prioritise the elucidation of the precise functions performed by transgenic BeSUS in Bambusaemeiensis or Arabidopsisthaliana, with particular emphasis on sucrose metabolism, responses to environmental stressors, and the process of cellulose synthesis. The complex mechanisms behind the synthesis of cellulose and lignin in bamboo are influenced by a combination of genetic factors and environmental conditions. The regulation of cellulose-producing genes in Bambusaoldhamii is influenced by several factors such as light intensity, fluctuations in temperature, and nutrition availability [156]. The process of lignin synthesis in bamboo is influenced by various factors, including the age of the plant, specific tissue types, and external stresses such as water scarcity or pest infestations [157]. A thorough comprehension of these mechanisms in bamboo has the potential to facilitate novel applications and advancements in materials.

- **Deposition of the Secondary Cell wall and Flowering:** The development of secondary cell walls in woody plants plays a vital role in their growth and maturation [158]. The MYB family of transcription factors (TFs) plays a crucial role in various biological processes, such as cellular development and structural organisation [159]. A total of 85 PeMYB genes were identified in the species Phyllostachys edulis[16]. The utilisation of RNA sequencing facilitated the identification of these genes in several plant tissues, hence suggesting their involvement in the formation of the

secondary cell wall. Moreover, a quantitative real-time polymerase chain reaction (qRT-PCR) research revealed the significant upregulation of 12 PeMYB genes in association with the biosynthesis of secondary cell walls. Furthermore, the NAC family of transcription factors (TFs) has been discovered to regulate a multitude of genes that are linked to the process of secondary cell wall construction in Phyllostachys edulis[16]. The ongoing investigation focuses on the complex interaction between genes and signalling pathways that govern the process of secondary cell wall formation in bamboo.

The prolonged flowering cycles exhibited by several bamboo species, with some enduring for as long as 120 years, have generated scientific interest regarding the genetic mechanisms governing the duration and timing of flowering events. A novel gene, DlEMF2, derived from Dendrocalamus latifolia, upon introduction of this gene into Arabidopsisthaliana plants, was seen to have accelerated flowering patterns, so indicating the involvement of DlEMF2 in the transition from vegetative to reproductive phase[160]. In a study investigating the expression patterns of the FLOWER LOCUS T (FT) gene, known for its role in promoting blooming, as well as the TERMINAL FLOWER 1/CENTRORADIALIS (TFL1/CEN) gene, which acts as a suppressor of flowering[14]. The two bamboo species chosen for this investigation were Phyllostachysmeyeri and Shibataeachinensis. The results of their study revealed that the expression of the FT gene reached its highest level at full blooming and afterwards declined gradually, whereas the TFL1/CEN gene exhibited continuous expression in inflorescences. This observation implies a plausible involvement of both genetic factors in the regulation of bamboo flowering. Further investigation into the pivotal genes that have an impact on the photoperiodic pathway in Bambusatulda[161]. They successfully identified multiple genes that are related with both the circadian clock and floral pathways. The study conducted by the researchers yielded valuable insights into the control of these genes through photoperiodic mechanisms, as well as their crucial role in the process of flowering. Nevertheless, the precise processes that govern the process of bamboo flowering continue to be perplexing, mostly because to its unpredictable nature, intricate genetic restrictions, and ecological ramifications.

V. BIO-ENERGY PRODUCTION USING BAMBOO FEEDSTOCK

Bamboo exhibits considerable versatility and renewability as a resource, since it can be effectively transformed into several energy forms, leveraging its abundant lignocellulosic composition. The energy forms encompassed within this category consist of bioethanol, bio-oil, biogas, and biochar. Bamboo possesses a substantial amount of lignocellulose, rendering it a highly promising candidate for the generation of bioethanol. The production process generally encompasses three primary stages: pretreatment, which involves the breakdown of the intricate bamboo structure to enhance the accessibility of cellulose; hydrolysis, wherein enzymes facilitate the conversion of cellulose into simple sugars, predominantly glucose; and fermentation, during which microorganisms, typically yeast, convert these simple sugars into ethanol. Bioethanol, which is derived from renewable sources, serves as an environmentally friendly alternative to petrol.

Furthermore, apart from the production of bioethanol, bamboo has the potential to undergo conversion into bio-oil utilising several techniques such as hydrothermal liquefaction and pyrolysis. Hydrothermal liquefaction is a technique that use water at elevated pressure and temperature to facilitate the conversion of bamboo into oil, mirroring the natural mechanisms involved in the formation of crude oil. In contrast, pyrolysis is a thermal decomposition process wherein bamboo is subjected to elevated temperatures in an oxygen-depleted environment, resulting in the disintegration of its molecular structure into a composite of gaseous compounds, liquid substances (such as bio-oil), and residual solid matter.

Bamboo has the potential to serve as a source for biogas production, consisting mostly of methane (CH4) and carbon dioxide (CO2). The process commonly employed for this purpose involves anaerobic digestion, wherein bacteria decompose organic material, such as bamboo, in an oxygen-deprived environment. The biogas produced can serve as a viable energy source for applications such as heating or the generation of electricity.

In addition, bamboo has the potential to undergo hydrothermal carbonization or pyrolysis processes, resulting in the production of biochar. The hydrothermal carbonization method involves the conversion of bamboo into a durable material with a high carbon content through the application of elevated pressure and temperature in the presence of water. Biochar can also be generated as a byproduct through the process of pyrolysis. Biochar is a valuable commodity that possesses the potential to serve as a soil amendment, so enhancing soil fertility and facilitating carbon sequestration. Alternatively, it can also be utilised as a fuel source owing to its considerable energy density.

The utilisation of conversion technologies has the capacity to harness the sustainable attributes of bamboo, positioning it as a noteworthy and environmentally friendly source of clean energy solutions[162]. Each of these energy types presents distinct advantages and applications, rendering bamboo an increasingly appealing choice in the pursuit of renewable and sustainable energy alternatives.

1. **Biochemical Composition of Bamboo Species:** Bamboo is commonly categorised into two distinct classifications: woody and herbaceous. The utilisation of woody bamboo biomass as the principal source of raw material is crucial for the production of several forms of energy and other commodities. Several taxa of bamboo, including Bambusa, Dendrocalamus, Phyllostachys, and a few others, are frequently employed in biomass generation due to their favourable attributes. The morphological traits observed in these species suggest their capacity to generate a significant quantity of individual bamboo biomass, as outlined in.

   The diversity of bamboo species is evident in their physical qualities, physiological traits, and biochemical makeup. As an example, it is worth noting that woody bamboos generally possess a lignocellulose content over 70%. This particular characteristic plays a significant role in influencing the manner in which they are processed for the production of biofuels and several other commodities. The considerable lignocellulose content present in woody bamboo renders it a highly suitable primary resource for the manufacturing of bioethanol, bio-oil, biogas, and biochar, owing to its capacity to be efficiently decomposed into fermentable sugars or transformed into alternative energy sources.

Furthermore, bamboo species exhibit significant variations in their photosynthetic properties, in addition to their morphological and biochemical distinctions. This aspect plays a crucial role in determining their growth rates and overall biomass production. Sympodialbamboo species demonstrate the most elevated rates of photosynthesis, with monopodial bamboo and mixed bamboo species following suit[163]. The observed disparities in photosynthetic rates between distinct bamboo species are anticipated to exert an impact on their growth patterns, biomass productivity, and eventually their appropriateness for diverse industrial uses, encompassing energy generation.

There are notable variations in morphological traits and biochemical composition among different species of bamboo, which have a discernible impact on their use as a primary resource for energy generation and various other applications. The aforementioned distinctions hold significant implications for researchers and industries engaged in the exploration of bamboo's potential as a sustainable and renewable resource.

Table 3: Composition analysis of bamboo species.

Species	Holocellulose	Lignin	Ash	References
Bambusa tulda	72.89	18.39	NA	[164]
Dendrocalamus giganteus	61.95	25.92	NA	[165]
Bambusa cacharensis	65.50	26.50	NA	[166]
Bambusa chungii	69.83	22.68	NA	[38]
Dendrocalamus sinicus	63.33	29.70	NA	[167,168]
Gigantochloa Scortechinii	67.39	28.10	<3.00%	[43]
Neosinocalamus affinis	62.69	28.20	NA	[168]
Phyllostachys edulis	66.00 -78.00	24.00–26.00	1.30 – 2.00	[169]
Pseudosasa amabilis	65.49	21.89	1.17	[170]
Pleioblastus chino	63.44	24.98	1.46	
Yushania alpina	58.94	25.27	3.77	[23]
Dendrocalamus latiflorus	65.52	26.19	2.96	[171]
Polystichum makinoi	68.22	28.78	1.75	
Phyllostachys edulis	64.96	28.80	1.73	
Pleioblastus chino	63.44	24.98	1.46	[170]

2. **Bamboo as a Source for Bioethanol and Solid Biofuels:** The utilisation of bamboo as a feedstock for bioethanol production is appealing for several reasons. Firstly, bamboo is classified as a non-food crop, which eliminates concerns related to diverting resources

away from food production. Additionally, bamboo possesses a significant amount of lignocellulose, a key component for the development of second-generation biofuels. These characteristics make bamboo a prospective candidate for the production of bioethanol [172]. Nevertheless, the inherent resistance and substantial lignocellulose composition of bamboo require supplementary pretreatment procedures in order to enhance the digestibility of its biomass. The implementation of these measures has the potential to diminish the economic viability of second-generation bioethanol production. The efficiency of converting lignocellulosic biomass into bioethanol is subject to various parameters, including the concentration of lignin, cellulose, hemicellulose linkages, and the crystalline structure. These characteristics collectively impact the digestibility of the biomass.

The production of bioethanol from lignocellulosic biomass involves a three-step process, including pretreatment, enzymatic hydrolysis, and fermentation. Pretreatment has a crucial role in the alteration of the crystalline structure of lignocellulose, the elimination of lignin and hemicellulose, and the enhancement of the cellulase-cellulose interaction by enlarging the contact area. Cellulose can be converted into fermentable sugars, such as glucose, through the process of enzymatic hydrolysis, which is assisted by the action of cellulase. Following this, a range of microorganisms are utilised to undergo the process of fermenting glucose into ethanol [173].

At present, bamboo is being utilised as a primary resource for the manufacturing of ethanol on a significant scale in several nations. The Numaligarh Refinery, located in Assam, India, is known to process approximately 500,000 tonnes of fresh bamboo on a yearly basis for the purpose of manufacturing biomass products. Notably, the refinery achieves a bioethanol production output of up to 49,000 tonnes. The residual waste generated post-production has the potential to be utilised as a renewable energy source by combustion, hence generating power [174].

The initial phase of the bamboo biomass to bioethanol conversion process, known as the pretreatment step, plays a crucial role in determining the effectiveness of the subsequent enzymatic hydrolysis. The process of converting lignocellulose into ethanol necessitates the combined implementation of saccharification and fermentation techniques. The process of enzymatic saccharification, facilitated by the action of cellulase, offers several benefits including a high conversion efficiency and minimal formation of unwanted by-products[175]. Nevertheless, the exorbitant expense associated with enzymes and the challenges in effectively regulating the quantity of enzymes employed can impose constraints on its utilisation. Chemical hydrolysis exhibits greater sensitivity to temperature and reaction time requirements[157].

Fermentation is a biological process wherein glucose and xylose serve as the key substrates for the conversion into bio-alcohols. The process is commonly conducted by microorganisms such as Saccharomycescerevisiae[176], Clostridium beijerinckii[177], Klebsiellaoxytoca[178], and Bacillus subtilis [179]. The selection of the fermentation method is a pivotal stage in the process, encompassing distinct hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), simultaneous saccharification and co-fermentation (SSCF), and consolidated bioprocessing (CBP) [180].

Numerous investigations have been conducted to explore hydrolysis and fermentation techniques for the conversion of bamboo. A comparison was made between the performance of simultaneous saccharification and fermentation (SSF) and separate hydrolysis and fermentation (SHF) processes for pretreatment bamboo using hydrogen peroxide and glacial-acetic acid[179]. The findings of the study indicated that SSF resulted in a slightly higher ethanol production (80.3%) compared to SHF (78.0%). A 13% enhancement in bioethanol production was achieved by the implementation of a sequential fermentation technique including the utilisation of Saccharomycescerevisiae and Scheffersomycesstipitis yeast[181].

The substantial lignocellulose composition of bamboo indicates its significant potential in the realm of bioethanol generation. Nevertheless, in practical application, the predominant portion of the expenses is attributed to the costs associated with pretreatment and fermentation procedures [182]. Commercial pretreatment processes must satisfy certain criteria, such as the prevention or minimal development of inhibitors, minimal consumption of water and energy, and so on. Small-scale bamboo bioethanol manufacturing systems face difficulties in meeting the demands of industrial production. Hence, it is imperative to conduct additional research in order to advance the technology for bamboo bioethanol production, enhance the effectiveness of pretreatment and fermentation procedures, and optimise the separation techniques to maximise the utilisation of bamboo biomass [180]. The latest developments in bamboo pretreatment techniques utilised in the production of bioethanol can be seen in **Table 4**.

Table 4: Biochemical conversion of bamboo species

Bamboo species	**Pretreatment condition**	**Saccharification**	**Sugar content (%)**	**Alcohol yields (g/L)**	**References**
Dendrocalmus sinicus	The reaction was conducted at a temperature of 70°C for a duration of two hours, utilising NaOH, sodium sulphite, and formaldehyde as reactants.	Cellic CTec2 of 2 Filter Paper Unit/g and 5 Filter Paper Unit/g with a substrate content of 5% (w/v) at 50°C for 72 hours	89.60	13.26	[167]
Dendrocalmus sinicus	Treatments methods include combining choline chloride and oxalic acid at	20 Filter Paper Unit/g cellulase at 5% (w/v), 50°C for 72 hours, and substrate concentration	85.71		[183]

	110–140°C for 6 hours and hydrothermal treatments at 130°C.				
Phyllostachys edulis	The green liquor was prepared by subjecting it to a temperature of 166.41°C for a duration of 28 minutes. This process was carried out in a steam explosion reactor with a capacity of 5 L, which was operated at a temperature of 213.30°C and a pressure of 2.5 MPa for a period of 5 minutes	Under the conditions of 5% substrate content (w/v), a temperature of 50.00 °C, and a duration of 48 hours, the cellulase activity was determined to be 21.20 Filter Paper Units per gramme, while the xylanase activity was found to be 13.44 Units per gramme	100.00	20.3	[184]
Phyllostachys edulis	NaOH, was employed in an acid-catalyzed steam pretreatment process at a temperature of 190°C for durations of 5, 10, and 15 minutes.	CellicCTec3 and B-glucosidase preparation loading at 50.00 °C for 72 hours at 5% and 20% substrate content (w/v).	85.8	50.1	[176]
Phyllostachyspubescens	30g DES pretreatment 90-130°C	500 mg substrate at 50°C for 6–48 hours with cellulase of 15 Filter Paper Unit/g.	96.08		[185]

Dendrocalmus sinicus	Hydrogen peroxide-acetic acid (HPAC) 60°C for 2h, NaOH 40°C for 2h	The cellulase enzyme, specifically Cellic CTec2, was utilised at a concentration of 6 Filter Paper Units per gramme with a substrate concentration of 5% (w/v) for a duration of 72 hours	83.66	16.54	[33]
Dendrocalamus giganteus			82.42	15.78	
Neosinocalamus affinis	Mechanically treated, alkaline hydrogen peroxide	15 Filter Paper Unit/g- glucan and 150U/g-xylan t 2.5%substrate concentration (w/v) for 72h	93.05		[35]
Phyllostachys edulis	The samples were subjected tohydrogen peroxide-acetic acid (HPAC) at a temperature of 60°C for a duration of 2 hours in the presence of NaOH. Additionally, another set of samples were exposed to a temperature of 40°C for the same duration.		53.57		
Bambusa lapidea	HPAC solution was subjected to a temperature range of 40-80°C for a duration of 2 hours	The cellulase activity was measured to be 6 Filter Paper Units per gramme at a substrate concentration of 5% (w/v) and a	82.53	14.45	[32]

		temperature of 50°C for a duration of 72 hours			
Dendrocalamus sinicus	HPAC solution was subjected to a temperature range of 40-80°C for a duration of 2 hours	The cellulase activity was measured to be 6 Filter Paper Units per gramme at a substrate concentration of 5% (w/v) and a temperature of 50°C for a duration of 72 hours	83.66	16.54	[32]
Dendrocalamus giganteus	HPAC solution was subjected to a temperature range of 40-80°C for a duration of 2 hours	The cellulase activity was measured to be 6 Filter Paper Units per gramme at a substrate concentration of 5% (w/v) and a temperature of 50°C for a duration of 72 hours	71.48	10.17	[32]
Neosinocalamus affinis	HPAC solution was subjected to a temperature range of 40-80°C for a duration of 2 hours	The cellulase activity was measured to be 6 Filter Paper Units per gramme at a substrate concentration of 5% (w/v) and a temperature of 50°C for a duration of 72 hours	81.25	11.78	[32]
Dendrocalamopsis oldhamii	A solution containing 30% hydrogen peroxide	The cellulase activity was measured at 15 Filter Paper Units	43		[186]

Bambusa multiplex	(H_2O_2) was subjected to a temperature of 20°C for a duration of minutes. Additionally, a quantity of 60 grammes of ammonia was exposed to a temperature of 130°C for a period of 20 minutes	per gramme, the 6-glucosidase activity was measured at 64 Cellulase Glucose Units per gramme, and the xylanase activity was measured at 1000 International Units per gramme. The enzymatic reactions were conducted at a temperature of 50°C for a duration of 72 hours	63		

The application of bamboo biomass for the manufacture of solid biofuel has attracted significant interest within the industry due to its notable heating value (HCV) of 18 to 21 kJ/g, which exhibits low fluctuation across different bamboo species. The higher heating value (HCV) of bamboo surpasses that of other frequently utilised biomass sources, rendering it an appealing substitute for mitigating the issue of coal scarcity. Bamboo solid fuels provide notable environmental advantages as compared to alternative woody plant options, as observed from an ecological standpoint. According to a life cycle study, it was determined that the overall ecological impact associated with the manufacturing of charcoal utilising Bambusabalcooa was considerably reduced when compared to Tectonagrandis and Acaciaauriculiformis[187].

Pyrolysis processes, including torrefaction and carbonization, are frequently employed in the conversion process of raw bamboo into biochar of significant economic worth. The aforementioned procedures entail subjecting the raw bamboo material to a heat treatment conducted in an oxygen-depleted environment, resulting in the production of charcoal, bio-oil, and bio-gas. The pyrolysis temperature has a notable impact on the combustion properties of bamboo charcoal, as demonstrated by several studies. Additionally, researchers have found that torrefaction and carbonization processes are beneficial in enhancing the calorific value of bamboo biomass.

The combustion reactivity of bamboo residue biofuel subjected to hydrothermal carbonization (HTC) treatment has been observed to be superior to that of wet torrefaction and dry torrefaction methods. The physical characteristics of bamboo solid fuels, including water absorption, durability, fineness, total calorific value, combustion rate, and exothermic rate, exhibit an upward trend as the carbonization temperature rises. The carbonised pellets obtained satisfy the minimum criteria for commercial pellets.

Thermogravimetric analysis (TGA) and differential thermogravimetric analysis (DTA) are commonly employed techniques for the characterization of the combustion behaviour of bamboo. The combustion process of Bambusabalcooa can be categorised

into three stages, characterised by specific temperature ranges and rates of weight loss. The temperature ranges associated with the combustion phases of different bamboo species exhibit modest variations, as documented in several studies.

The observed substantial enhancement in the higher calorific value of bamboo following the processes of carbonization and torrefaction has the potential to yield favourable outcomes in terms of the synergistic effects of bamboo char mixed combustion and co-pyrolysis with other substances. The co-combustion of bamboo and coal is a prevalent fuel option that effectively mitigates carbon dioxide (CO2) emissions. Nevertheless, the precise nature of the interaction between coal and bamboo charcoal during co-combustion remains a subject of ongoing discussion, potentially contingent upon many material qualities and reaction conditions.

The co-pyrolysis of bamboo with a range of materials, including plastics, has attracted considerable attention in academic circles. In a recent study, the co-pyrolysis potential of bamboo sawdust in conjunction with linear low-density polyethylene was examined[188]. The researchers observed that the inclusion of bamboo sawdust resulted in an expedited degradation of plastic and an improved co-combustion mechanism. During co-pyrolysis experimentson disposable masks and bamboo residue, the occurrence of synergistic effects were noticed [189].

The exceptional performance of bamboo and plastic biofuels may serve as a crucial approach for addressing the present challenges associated with plastic waste management. The co-pyrolysis of bamboo with diverse materials, including pigeon pea stems, soap-stock, and rice husk, has demonstrated significant promise in the production of solid fuels. The utilisation of solid fuels derived from bamboo not only facilitates the co-combustion process with other substances but also enhances the efficacy of fuel combustion. When comparing bamboo biomass solid fuels to other biomass sources, such as microalgae, which predominantly utilise lipids for energy production, it is seen that the former does not contribute to the emission of NO_x pollutants. Hence, it is justifiable to anticipate that solid fuels derived from bamboo possess significant prospects for advancement.

Table 5: Synergistic co-combustion and co-pyrolysis of bamboo for energy and resource recovery.

	Species	**Materials**	**Reaction conditions**	**Observation**	**References**
Co-combustion	Bamboo residues	Wastewater generated from the dyeing process in the textile industry, as well as the accompanying sludge	20% O_2 /80% CO_2	A 55.09% reduction in SO_2 production and a 17.3% enhancement in co-combustion performance was observed	[190]

	Bamboo residues	Gasification slag, bituminous coal	Air	Interactions that are both Synergistic and antagonistic during co-combustion	[191]
	Bambusa balcooa	Coal with high ash content	Oxidizing atmosphere	Bamboo that is four years old and torrefied has the best coal combustion qualities	[191]
Co-pyrolysis	Bamboo residues	Heavy bio-oil	N_2	A bio-oil yield of 61.84% with a higher heating value (HHV) of 27.75 MJ/kg can be achieved by employing a 20% raw bamboo feedstock at a temperature of 640°C	[40]
	Moso bamboo	Heavy bio-oil	N_2	Yield of 23.14% by weight and 41.18 % by volume of H_2 + CO can be derived from 50% bamboo at 550°C	[39]
	Bamboo residues	Polyethylene, polypropylene, polystyrene, and polyethylene terephthalate	N_2	Optimal yields of biochar was produced with the addition of 10% plastic powder at 623K	[192]

	Bamboo residues	Stalks derived from Cajanus cajan	N_2	It was observed that a pyrolysis temperature of 600°C resulted in the production of biochar of superior quality	[193]
	Phyllostachys edulis	Cunninghamia sp.	N_2	The co-pyrolysis carbon of bamboo and Cunninghamia sp. demonstratedhigh calorific value (33.85 MJ/kg)	[194]
	Phyllostachys edulis	Soapstock	N_2	The synergistic impact of the co-pyrolysis process involving bamboo and soapstock subsequent to wet torrefaction	[194]
	Phyllostachys edulis	Heavy and light bio-oil	N_2	The co-pyrolysis of bamboo and heavy bio-oil exhibited synergistic effects during the biochar preparation process	[42]
	Bamboo residues	Sewage sludge	N_2	The co-pyrolysis process involving the combination of sewage sludge and bamboo sawdust at a temperature of 700°C resulted in the production of biochar that exhibited exceptional stability	[42]

VI. CONCLUSION

Bamboo stands as a remarkable botanical entity that flourishes in various geographical environments, ranging from tropical to temperate areas, displaying its adaptability and resilience. The plant exhibits unique characteristics, including its abundance of branches, woody composition, and rapid rate of growth, which distinguish it from other members of the Poaceae family.

The versatile utility of bamboo extends beyond conventional applications to encompass contemporary, environmentally-friendly uses, thereby establishing it as a valuable ecological resource commonly known as "green gold." Bamboo, as a bioresource, exhibits significant potential in the realm of renewable energy, presenting a carbon-neutral substitute for fossil fuels. The rapid expansion of bamboo cultivation, along with its capacity to be transformed into diverse forms of energy, has generated significant international attention. Nevertheless, the increase in demand has raised apprehensions regarding the excessive exploitation and its potential consequences on the natural bamboo populations.

The difficulties associated with bamboo propagation have spurred advancements in tissue culture techniques, which have proven particularly advantageous for the purposes of extensive cultivation and the preservation of genetic resources. Furthermore, the application of contemporary biotechnology has facilitated the investigation of the genetic composition of bamboo. However, the manipulation of bamboo's genetic material remains intricate owing to its monocotyledonous characteristics.

The genomic discoveries pertaining to bamboo have shed light on various aspects of its biology, including its growth patterns, lignin synthesis, flowering behaviour, and stress responses. These findings present opportunities for utilising the distinctive characteristics of bamboo in the realms of environmental preservation and economic advancement. Through a comprehensive comprehension of the complex interactions between genes and transcription factors, it is conceivable that we could potentially customise the growth and characteristics of bamboo to align with specific requirements.

Within the field of bioenergy, bamboo emerges as a commendable environmentally conscious substitute, primarily due to its expeditious growth rate, substantial cellulose composition, and noteworthy capacity for carbon sequestration. However, it is imperative to implement sustainable management strategies in order to effectively reconcile the commercial value of bamboo with its crucial role in preserving biodiversity and forest ecosystems.

As we further explore the potential of bamboo, it becomes apparent that this multifaceted plant possesses the means to tackle a multitude of challenges, ranging from the generation of sustainable energy to the preservation of ecological systems. Ongoing research, innovation, and the implementation of sustainable practises are crucial in order to fully harness the wide range of benefits that bamboo provides.Through collaborative efforts, we can cultivate a greener, more sustainable future by harnessing the potential of this "green gold" that nature has bestowed upon us.

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