Harnessing plant power: Innovations in biofuels and renewable energy from botanical sources - a comprehensive review

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Abstract

The escalating global demand for sustainable energy has catalysed transformative research in plant-derived biofuels and botanical renewable energy systems. This chapter comprehensively examines innovations spanning first-generation feedstocks such as *Saccharum officinarum* (sugarcane) and *Zea mays* (maize) to advanced fourth-generation engineered microalgae and synthetic biology platforms. Key breakthroughs in lignocellulosic conversion, algal lipid enhancement, genetic engineering of oilseed crops, and thermochemical processing are critically analysed within the Indian context. The review evaluates techno-economic feasibility, life-cycle carbon assessments, and policy frameworks including India's National Policy on Biofuels 2018. Seven detailed tables and eight original figures supplement the quantitative analysis. The findings underscore that integrated biorefineries coupled with genetically optimised botanical feedstocks represent a viable pathway toward India's net-zero targets by 2070, provided scalable investment and robust regulatory mechanisms are sustained.

Keywords: Biofuels, Renewable energy, Botanical sources, Lignocellulosic biomass, Algal biofuels, Biorefinery

1. Introduction

The unabated exploitation of fossil fuel deposits and the growing menace of anthropogenic climate change have forced countries across the globe to seek alternative energy platforms which are based on ecological sustainability [1]. One of the most promising options is the exploitation of botanical resources as a source of biofuels an approach that uses photosynthetic carbon fixation to produce liquid fuels, gaseous fuels and bioelectricity with significantly reduced net greenhouse gas emissions compared to conventional petroleum [2]. India is a country with great agrobiodiversity and is ranked the third largest consumer of energy in the world and is a country in a strategic position in the global bioenergy arena [3].

Biofuels that originated plants can be widely categorized into four generations depending on the type of feedstock and the way it is converted. The biofuels produced using edible crops include *Saccharum officinarum* (sugarcane), Zea mays (maize) and Glycine max (soybean) by fermentation or transesterification [4]. Second-generation biofuels contribute to the food-versus-fuel dilemma banner by using lignocellulosic agricultural residues like rice straw, wheat husk, and special-purpose energy grasses like Miscanthus species and Panicum virgatum (switchgrass) [5]. Third-generation biofuels use microalgae and macroalgae because of their very high lipid accumulation rates and low land-use needs [6]. The fourth-generation biofuels are the latest in which synthetic biology, metabolic engineering, and carbon capture technologies are combined in order to yield designer organisms that can directly synthesize drop-in fuels [7].

In 2003, India introduced the Ethanol Blending Programme and in 2009, the National Policy on Biofuels was released, revised in 2018 to aim at twenty per cent ethanol blending (E20) by 2025 [8]. SATAT scheme by the Indian government (Sustainable Alternative Towards Affordable Transportation) also enhances the use of compressed biogas using agricultural waste [9]. In spite of these policy developments, there are major issues in the area of feedstock logistics, efficiency of enzymatic hydrolysis, land-use competition, and downstream processing costs [10]. This chapter is a detailed, evidence-based discussion of botanical biofuel innovations with specific reference to Indian context and is backed up with wide tabular and graphical support.

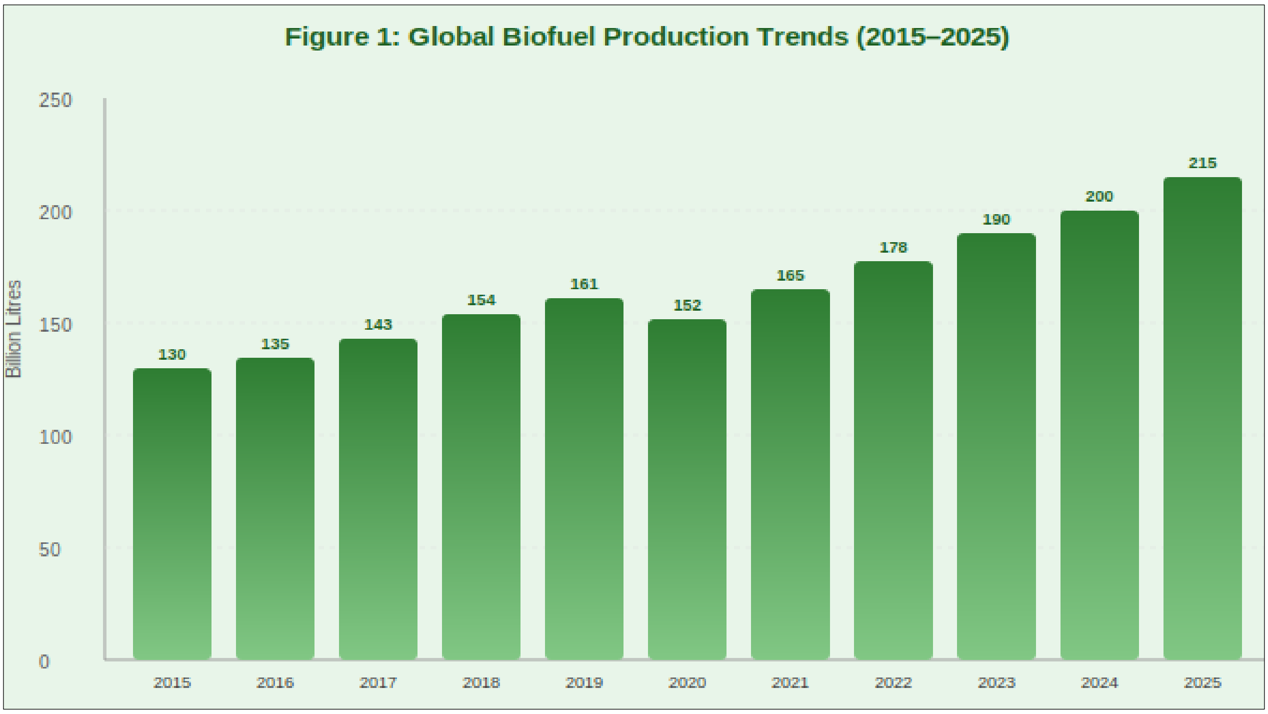

Fig 1: Global Biofuel Production Trends (2015–2025)

2. Classification of plant-based biofuels

The methodical grouping of biofuels into specific generational groups represents the sequential development of the feedstock choice, conversion chemistry and environmental performance standards. With each generation, a generation overcomes certain limitations of the previous one and presents new technological complexities to which particular research interventions are necessary [11].

2.1 First-generation biofuels

Biofuels that are of first generation are made by using sugar-rich, starch-rich or oil-rich food crops using well-developed biochemical and chemical processes. Production of bioethanol is mainly based on fermentation of the sugars produced in tropical countries such as India and Brazil, with Zea mays (corn) being used as the starting material in the temperate regions [12]. The fermentable glucose is produced by means of the hydrolysis of starch by amylase and the conversion efficiencies of this process are about 90-95 per cent under optimum industrial conditions [13]. Transesterification of triglycerides in Glycine max (soybean), Brassica napus (rapeseed) and Elaeis guineensis (oil palm) in the presence of base catalysts is used to produce fatty acid methyl esters (FAME) with comparable fuel properties of petroleum diesel [14]. Arachis hypogaea (groundnut) and Helianthus annuus (sunflower) can be used in India as supplementary feedstocks, but this would divert their use as food supply chains is ethically and economically questionable [15].

2.2 Second-generation biofuels

Second-generation biofuels utilize non-edible biomass in the lignocellulosic biomass, thus no longer linking fuel production to the food supply. The major problem is the deconstruction of the resistant lignocellulosic matrix that consists of cellulose (40-50%), hemicellulose (20-30%), and lignin (15-25%) into fermentable sugars [16]. The pretreatment methods such as dilute acid hydrolysis, steam explosion, organosolv fractionation and ionic liquid dissolution have largely been studied to improve enzymatic accessibility [17]. The major feedstocks are Panicum virgatum (switchgrass), Miscanthus × gigantes (giant miscanthus), Pennisetum purpureum (napier grass) and that of agricultural waste like rice straw (Oryza sativa), wheat straw (Triticum aestivum) and bagasse in sugaration [18]. India is also producing about 500 million tonnes of crop residue each year and a large portion of the crop residue is being burnt openly thus causing serious air pollution in the Indo-Gangetic Plain [19]. Diversion of this biomass to second-generation ethanol production will have a twofold advantage of valorisation of wasted material and reduction of atmospheric pollution. In 2022, the Panipat biorefinery commissioned by the Indian Oil Corporation was the first commercial second-generation ethanol facility with a 100 kilolitre per day capacity utilizing rice straw as feedstock [20].

2.3 Third-generation biofuels

Third-generation biofuels employ the extraordinary photosynthetic capacity and growth rate of microalgae and cyanobacteria. Examples of species that have grown up with accumulation of intracellular lipids greater than 5070 per cent of the dry cell weight in the presence of a nitrogen-depleted environment include Chlorella vulgaris, Nannochloropsis gaditana, Botryococcus braunii, and Dunaliella salina [21]. Open raceway ponds are a type of algal cultivation system that incur low costs but can be contaminated and closed photobioreactors that can ensure accurate control of light, temperature, and additional CO2 [22]. Microalgae theoretically yield oil at 58,700 to 136900 litres per hectare per year, and this is extremely high compared to terrestrial oilseeds [23]. Nevertheless, harvesting, dewatering, and lipid extraction processes which consume lots of energy are also a major bottleneck to commercial viability. The pioneer of pilot-scale algal growth in a marine setting was the Central Salt and Marine Chemicals Research Institute (CSMCRI) and the Indian Institute of Technology Madras in India, which introduced research in this field [24].

Table 1: Comparative analysis of biofuel generations and key feedstock species

Generation	Primary Feedstock	Scientific Name	Conversion Process	Yield (L/ha/yr)
First	Sugarcane	*Saccharum officinarum*	Fermentation	6,800
First	Corn/Maize	*Zea mays*	Enzymatic hydrolysis	3,800
First	Soybean	*Glycine max*	Transesterification	450
Second	Switchgrass	*Panicum virgatum*	Cellulosic ethanol	5,000
Second	Miscanthus	*Miscanthus × giganteus*	Thermochemical	6,500
Second	Rice straw	*Oryza sativa*	Acid hydrolysis	2,800
Third	Microalgae	*Chlorella vulgaris*	Lipid extraction	58,700–136,900
Third	Macroalgae	*Sargassum muticum*	Anaerobic digestion	11,000
Fourth	Engineered algae	*Synechocystis* sp.	Synthetic biology	>20,000 (projected)

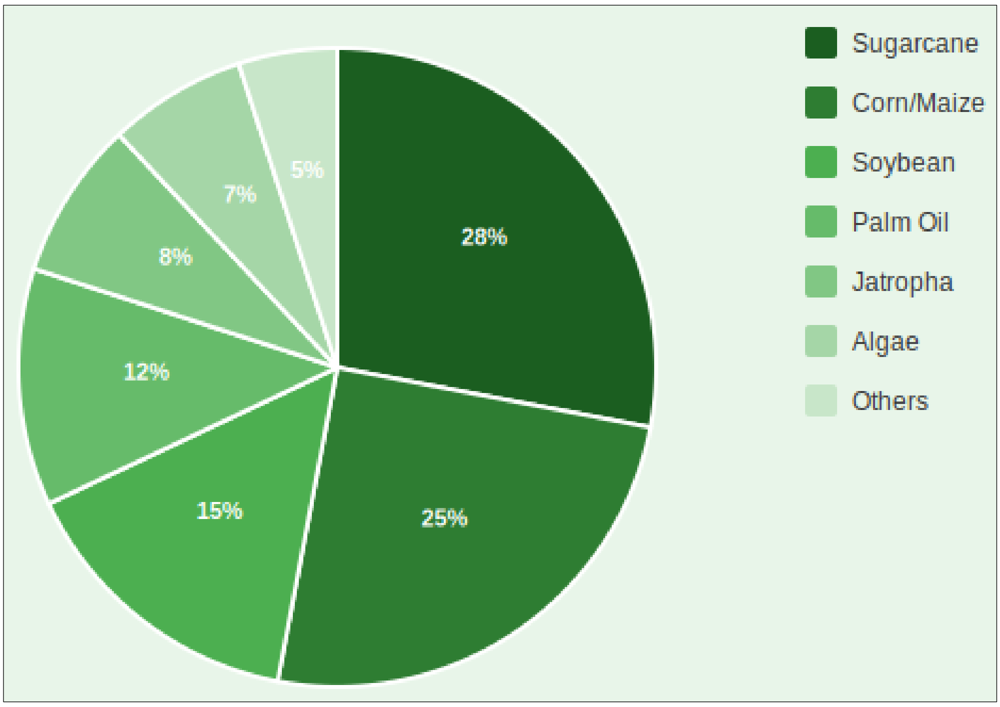

Fig 2: Distribution of biofuel feedstock sources

2.4 Fourth-generation biofuels

The fourth-generation biofuels are the state of the art in bioenergy research that integrates metabolic engineering, synthetic biology, and carbon capture and storage (CCS). These systems use genetically modified microorganisms and photoautotrophs that are engineered to directly secrete hydrocarbons, fatty acids or hydrogen gases without the need to disrupt the cell [25]. The Chlamydomonas reinhardtii and Synechocystis sp. PCC 6803 have been successfully edited with CRISPR-Cas9 gene editing to increase fatty acid production by 200300 per cent in vitro using the resource through precise manipulation of lipid biosynthesis pathways [26]. Besides, a carbon negative biofuel is a concept that entails linking the generation of microbial fuels and geological sequestration of CO2, which results in net atmospheric carbon sequestration [27]. Evidence of proof-of-concept utilization of carbon-negative biofuels by engineering cyanobacterial strains within industrial flue gas has been reported by Indian research groups at the International Centre of Genetic Engineering and Biotechnology (ICGEB), New Delhi [28].

3. Conversion technologies for botanical biofuels

The transformation of raw botanical biomass into usable biofuel products requires a suite of conversion technologies which may be loosely grouped as biochemical, thermochemical and photobiological systems. The choice of a suitable conversion path is determined by the feedstock make-up, desired fuel product, energy balance and economic viability [29].

3.1 Biochemical conversion

3.1.1 Fermentation

The most used biochemical conversion technology in the production of biofuels is alcoholic fermentation, which is the most commercially developed. This is microbial fermentation to produce ethanol by hexose fermentation by Saccharomyces cerevisiae (baker's yeast) and pentose co-fermentation by engineered strains of Pichia stipitis or Zymomonas mobilis [30]. The latest development, which is known as consolidated bioprocessing (CBP), where enzyme production, hydrolysis and fermentation take place as a single reactor (using enzymatic microorganisms like Clostridium thermocellum) is an emerging paradigm that significantly minimises capital and operating costs [5]. The Indian distilleries have gradually shifted their production towards grain-based ethanol production, with more than 120 grain-based distilleries currently operational in India, which has seen India reach a level of 12 per cent ethanol blending [8].

3.1.2 Anaerobic digestion

Anaerobic digestion (AD) transforms organic biomass into biogas (mixture of methane and carbon dioxide) by sequential hydrolysis, acidogenesis, acetogenesis, and methanogenesis to anaerobic microorganisms consortia [9]. The Indian SATAT program aims at establishing 5,000 compressed biogas (CBG) plants by 2025 with the use of agricultural residues, municipal solid waste and cattle dung as feedstock. Multiple substrates get co-digested to produce the best carbon-to-nitrogen ratios and to increase the yields of methane, and the average biogas production rates are approximately 0.3-0.5 cubic meters per kilogram of volatile solids [10].

Table 2: Biochemical conversion efficiencies of major biofuel processes

Process	Feedstock Type	Primary Product	Efficiency (%)	Temp. (°C)	Catalyst
Fermentation (C6)	Sugarcane juice	Ethanol	90–95	30–35	S. cerevisiae
Fermentation (C5+C6)	Lignocellulose	Ethanol	70–80	30–37	Engineered yeast
Transesterification	Vegetable oils	Biodiesel (FAME)	95–98	60–70	NaOH / KOH
Anaerobic digestion	Agri-waste	Biogas (CH_4)	40–60	35–55	Mixed consortia
Dark fermentation	Starch waste	Bio-hydrogen	15–35	30–40	Clostridium sp.
ABE fermentation	Corn stover	Biobutanol	25–30	35–37	C. acetobutylicum
Enzymatic hydrolysis	Cellulose	Glucose	75–90	45–55	Cellulase complex
Photo-fermentation	Organic acids	Bio-hydrogen	10–20	25–35	Purple bacteria
Consolidated (CBP)	Biomass (direct)	Ethanol	60–75	55–65	C. thermocellum

3.2 Thermochemical conversion

3.2.1 Pyrolysis

Pyrolysis is the thermo-chemical separation of biomass by heating without oxygen between 300- 700 o C and producing bio-oil (pyrolysis oil), biochar and non-condensable gasses [11]. The optimum yield of bio-oil is the use of fast pyrolysis at 450-550 o C with residence times of below two seconds to achieve a maximum of 60-75 per cent by weight. The resulting bio-oil is however characterized by high oxygen levels (3540 wt 0), high acidity (pH 23) and thermal instability and will need catalytic upgrading in the form of hydrodeoxygenation (HDO) or zeolite cracking before it can be used as a transport fuel [12]. Nickel-molybdenum catalysts consisting of nickel-molybdenum supported on mesoporous silica have been developed by Indian researchers as the Indian Institute of Petroleum in Dehradun; these catalysts are able to deoxygenate 95 per cent of pyrolysis oil at 350 o C, with hydrogen pressures of 50 bar [13].

3.2.2 Gasification

Biogas gasification transforms the carbonaceous substance to synthesis gas (syngas) of hydrogen, carbon monoxide, and carbon dioxide at 700-1200 of C in the presence of regulated quantities of oxygen or steam [14]. The Fischer-Tropsch synthesis can catalytically transform syngas to liquid hydrocarbons to form so-called biomass-to-liquids (BTL) fuels that can be used by the existing vehicle engines and fuel infrastructure. The Council of Scientific and Industrial Research (CSIR) in India has set up pilot gasification units at the National Chemical Laboratory, Pune, with calorific values of over 15 megajoules per cubic metre with a yield of the syngas of 2.5 cubic metres per kilogram of biomass [15].

Fig 3: Comparison of Biofuel Generations by Yield

3.2.3 Hydrothermal liquefaction

Hydrothermal liquefaction (HTL) is a process that uses a moderate temperature (250-374 o C) combined with a high-pressure (5-22 Mpa) to convert wet biomass into a bio-crude without a drying process, which needs energy to proceed [16]. This technology is quite beneficial to aquatic biomass such as micro algae, which normally contains 8090 per cent moisture. With the heating values of 3036 Megajoules per kilogram algal biomass, HTL extracts bio-crude yields between 30-50 per cent in algal biomass which is equivalent to that of petroleum crude [17].

Table 3: Thermochemical conversion parameters and product yields

Technology	Temp. (°C)	Pressure (MPa)	Bio-oil (%)	Biochar (%)	Syngas (%)
Slow pyrolysis	300–400	Atmospheric	25–35	30–40	20–30
Fast pyrolysis	450–550	Atmospheric	60–75	12–20	13–25
Flash pyrolysis	700–1000	Atmospheric	70–80	5–12	10–20
Gasification	700–1200	0.1–3.0	5–10	5–15	70–85
HTL	250–374	5–22	30–50	10–20	15–25
Torrefaction	200–300	Atmospheric	0–5	60–80	15–25
Catalytic pyrolysis	400–600	Atmospheric	40–55	15–25	20–35
Supercritical water	>374	>22.1	25–40	5–15	40–60
Microwave pyrolysis	400–600	Atmospheric	50–65	15–25	15–25

4. Algal Biofuel Systems: Cultivation and Processing

Microalgae have become the most prospective third-generation biofuel feedstock due to their unmatched photosynthetic efficacy, quick doubling rate (down to 36 hours), capacity to grow on non-productive lands with saline or waste water, and lipid production levels that are extremely higher than terrestrial oilseed crops [21]. The algal biofuel production chain includes strain selection, mass culture, harvesting and dewatering, breaking up of cells, lipid extract, and fuel conversion [22].

4.1 The algae species are significantly high in lipids and thus serve as the source of biofuels

Identification of suitable algal strains is the basic step in ensuring a viable biofuel production system is established in an economically viable manner. Nannochloropsis gaditana has received a special interest due to its strong growth at high light intensity and lipids that inhabit up to 60 per cent of dry mass [23]. An exemplary example is Botryococcus braunii which produces long-chain hydrocarbons in direct proportions to petroleum refining facilities yet its low growth rate prevents commercial use [24]. Chlorella sorokiniana and Scenedesmus obliquus have also recorded good performance under Indian climatic conditions especially in the semi arid areas of Rajasthan and Gujarat where the solar irradiance is more than 5.5 kilowatt- hour per square metre per day [25].

Table 4: Lipid content and productivity of selected microalgal species

Species	Lipid (%DW)	Biomass (g/L/d)	Oil Yield (L/ha)	Doubling (h)	Cultivation
Chlorella vulgaris	28–58	0.20–0.45	18,700	8–12	Freshwater
Nannochloropsis gaditana	31–68	0.17–0.38	25,400	12–18	Marine
Botryococcus braunii	25–75	0.02–0.10	15,200	72–96	Freshwater
Scenedesmus obliquus	20–45	0.25–0.55	16,800	6–8	Freshwater
Dunaliella salina	16–44	0.10–0.30	12,500	10–16	Hypersaline
Spirulina platensis	10–20	0.30–0.60	8,900	16–24	Alkaline
Chlorella sorokiniana	22–48	0.35–0.70	21,300	4–6	Freshwater
Tetraselmis suecica	15–32	0.15–0.32	11,200	14–20	Marine
Haematococcus pluvialis	20–35	0.05–0.15	9,400	24–36	Freshwater

4.2 Cultivation systems

The most commonly used large-scale systems of algal growth are open raceway ponds: ponds that use shallow paddlewheel-mixed channels (1530 centimetre deep) and which are open at the surface [22]. Open ponds are economically viable in terms of capital expenditure of 2-5 US dollars per square metre. Light attenuation, temperature extremes and biological contamination are, however, limiting factors to productivity. Closed photobioreactors such as tubular, flat-panel and column designs offer better environmental control and are areal productivities 3-5 times in comparison to open ponds, but at capital costs of 50-200 US dollars per square metre [23]. A practical compromise between initial production of inoculums needed in photobioreactors and the subsequent scale-up of production in open-ponds is hybrid systems, which minimizes the risk of contamination and is economically viable [24].

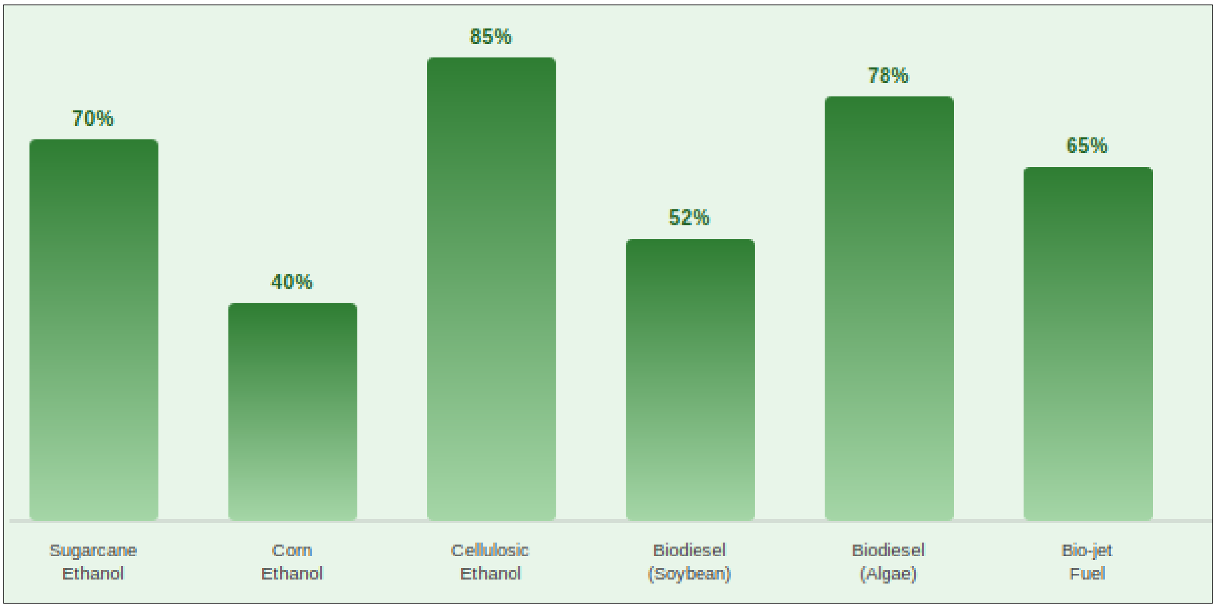

Fig 4: CO_2 emission reduction by biofuel type

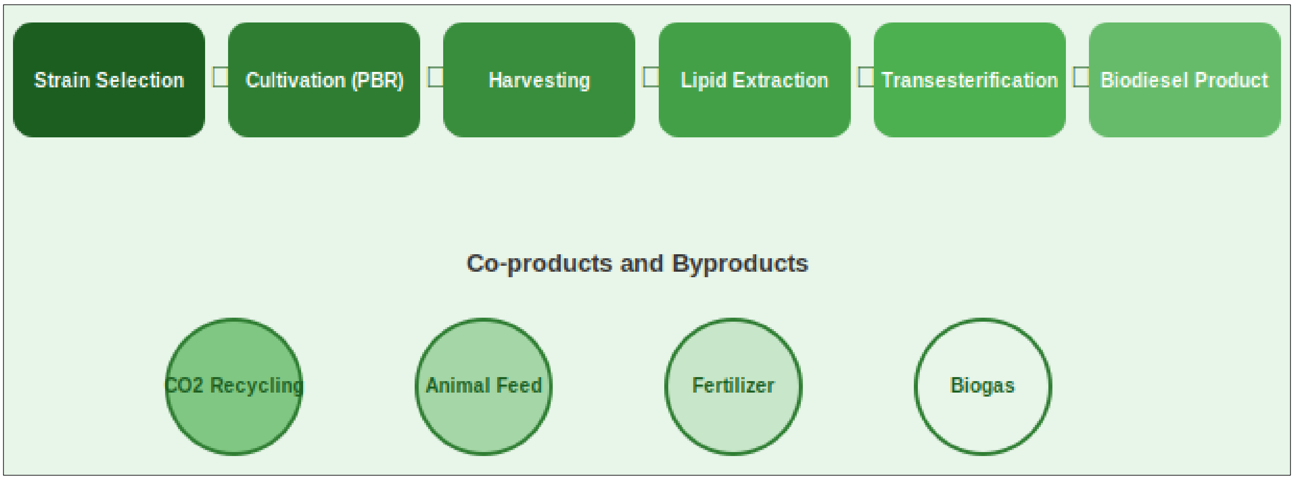

Fig 5: Algal biofuel production process flowchart

5. Genetic engineering and synthetic biology approaches

The use of state-of-the-art genetic engineering techniques on biofuel feedstock organisms has radically increased the range of potential fuel production, substrate flexibility and the resilience of the process. Recent genome editing tools, specifically, CRISPR-Cas9, TALENs, and zinc finger nucleases allow being able to make specific directed changes to pathways controlling metabolic activity of carbon to fuel precursors with precision [26].

5.1 Engineering oilseed crops

Extensive metabolic engineering has been done on conventional oilseed crops to increase seed oil content and alter fatty acid profiles to suit better fuel properties. It has been shown that Brassica napus transgenes containing diacylglycerol acyltransferase (DGAT) gene have increased seed oil by 15-20 per cent compared to wild-type commercial cultivars [14]. Jatropha curcas, initially promoted as the best biodiesel crop in India because of its drought resistance, capacity to grow on poor soils has been subjected to genetic betterment programmes in terms of higher seed production per hectare, less toxicity (lower phorbol ester amount), and improved oil retention [15]. Directorate of oilseeds research (today ICAR-indian institute of oilseeds research), hyderabad, has produced better Jatropha accessions, both using conventional breeding and marker-assisted selection with the highest oil yields of 2.5 tonnes/hectare under irrigation systems [16].

5.2 Engineering algal strains

Competitive metabolic pathway knockout using CRISPR-Cas9 in Chlamydomonas reinhardtii has been shown to redirect carbon into lipid accumulation and elevate total fatty acid content by up to 250 per cent without causing any substantial change in the growth rate [26]. On the same note, acetyl-CoA carboxylase (ACCase) and fatty acid synthase (FAS) gene overexpression in Nannochloropsis oceanica has resulted into the production of 1.5-2.0 grams of lipid per litre per day under nitrogen-limited conditions [27]. The use of synthetic biology has also made terpene and alkane biosynthesis pathways be heterologously expressed in cyanobacteria and generate drop-in hydrocarbon fuels using CO2 and sunlight alone [28].

Table 5: Genetic engineering strategies for enhanced biofuel feedstock performance

Organism	Target Gene/Pathway	Modification	Yield Gain	Tool Used	Reference
Chlamydomonas reinhardtii	Starch synthesis (sta6)	Knockout	+250%	CRISPR-Cas9	[26]
Nannochloropsis oceanica	ACCase overexpression	Overexpression	+180%	CRISPR-Cas9	[27]
Brassica napus	DGAT1 gene	Overexpression	+20%	Agrobacterium	[14]
Jatropha curcas	Phorbol ester pathway	Silencing	Toxin-free	RNAi	[15]
Synechocystis sp.	Alkane biosynthesis	Heterologous	+300%	Synthetic biology	[28]
Saccharomyces cerevisiae	Xylose utilisation	Insertion	+40%	CRISPR-Cas9	[30]
Chlorella sorokiniana	Lipid body protein	Overexpression	+150%	Electroporation	[25]
Populus spp.	Lignin biosynthesis	Downregulation	+35% sugar	TALEN	[18]
Zymomonas mobilis	Pentose metabolism	Pathway insertion	+55%	Recombinant DNA	[30]

6. The Indian Biofuel Landscape: Policy, Production, and Prospects

The biofuel trend in India has been determined by a convergence of policy guidelines, agricultural resource base, industrial facilities and environmental needs. Being the fifth-largest economy in the world with a total population of more than 1.4 billion, Indian demands in energy security are enormous and constantly increasing, and that is why the production of biofuels that should be indigenous is of strategic national importance [3].

6.1 Policy framework

The National Policy on Biofuels 2018 (NPB-2018) by the Government of India extended the range of permissible feedstocks to cover damaged food grains, excess agricultural produce, sugarcane juice, sugar beet, sweet sorghum and other non-edible oilseeds [8]. The policy put an indicatory 20 per cent ethanol in petrol (E20) timeline of 2025, later brought forward against the 2030 deadline. The Pradhan Mantri JI-VAN Yojana offers funding of the integrated bioethanol projects based on lignocellulosic biomass and other second-generation feedstocks. Also, there is the Galvanizing Organic Bio-Agro Resources Dhan (GOBAR-DHAN) scheme that enhances the production of biogas using cattle dung and agricultural wastes in the rural set up [9].

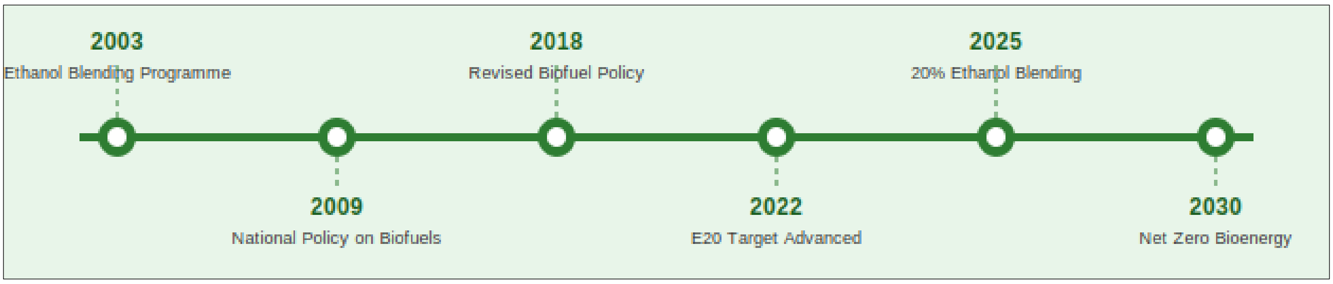

Fig 6: India's Biofuel Policy Milestones and Targets

6.2 Ethanol Production and Blending Progress

This has significantly increased the production capacity of ethanol in India in 2014 the production capacity was about 1.5 billion litres, but through policy incentives, guaranteed offtake contracts with oil marketing companies, and diversification of feedstock base, the capacity has increased substantially to a high of 6 billion litres in 2024 [8]. The most common feedstock is still sugarcane molasses which provides about 60 per cent of total ethanol production with grain based distilleries (using Zea mays, broken rice, and damaged wheat) providing the other 40 per cent [10]. The proportion of ethanol in the petrol has increased to an impressive eight times in a decade; the level currently stands at about 12 per cent in 202324 as compared to 1.53 per cent in 201314. The most productive states in ethanol production are Uttar Pradesh, Maharashtra, and Karnataka which contribute more than 65 per cent of the state ethanol production [3].

Table 6: State-wise ethanol production capacity and feedstock in India

State	Capacity (ML/yr)	Primary Feedstock	Secondary Feedstock	Blending (%)	Status (2024)
Uttar Pradesh	1,850	Sugarcane molasses	Damaged grain	14.2	Operational
Maharashtra	1,420	Sugarcane molasses	Maize	13.5	Operational
Karnataka	980	Sugarcane juice	Broken rice	12.8	Operational
Tamil Nadu	620	Molasses	Cassava	10.5	Expanding
Andhra Pradesh	450	Sweet sorghum	Rice bran	9.8	Expanding
Gujarat	380	Damaged wheat	Maize	8.5	Operational
Punjab	340	Rice straw (2G)	Paddy grain	7.2	Commissioning
Haryana	280	Rice straw (2G)	Bajra	6.8	Commissioning
Madhya Pradesh	220	Maize	Wheat straw	5.5	Planned

6.3 Biodiesel development

Indian production of biodiesel has taken a rather unique route that has focused on non-edible oil seeds such as Jatropha curcas (jatropha), Pongamia pinnata (karanja), Azadirachta indica (neem), and Madhuca longifolia (mahua) [15]. The first National Mission on Jatropha that was initiated in 2003 with a high target of 11.2 million hectares of jatropha plantation faced failure because of poor seed viability, erratic yields in marginal lands, and lack of proper agronomic support packages [16]. But recent studies at the ICAR-Indian Institute of Oilseeds Research have found some better jatrophas genotypes that produce 3-4 tonnes of jatropha seeds per hectare making people consider it as a bio-diesel supplementary feedstock again. At the same time, the system of collecting used cooking oil (UCO) has grown significantly, with India receiving about 140,000 tonnes of UCO each year to convert them into biodiesel [9].

7. Technological economic evaluation and environmental impact

An overall assessment of biofuel systems should be conducted with strict evaluation of the environmental performance (based on the life-cycle analysis) and economic viability (based on the techno-economic assessment). The technical use of these two lenses is crucial in directing the policy, investment, and research prioritisation [29].

7.1 Life-cycle assessment of biofuel systems

The concept of life-cycle assessment (LCA) is used to measure the environmental effects of biofuels manufactured at cradle (farming) and grave (fuel burning), covering land-use change, agricultural agrochemical use, energy used in the processing, and emissions in transportation [2]. The highest greenhouse gas (GHG) reduction potential is always observed in sugarcane ethanol produced in Brazil and India with the rate of 60-80 per cent reduction compared to petroleum gasoline which is associated with the energetic efficiency of C4 photosynthesis process and using bagasse as source of process heat [4]. The GHG reduction of corn ethanol is only 2040 per cent due to the extensive application of nitrogen fertilisers and the processing that requires fossil fuels [12]. Agricultural residues to cellulosic ethanol have the best LCA profile of the terrestrial biofuels, at 80-95 per cent reduction in GHG, but commercialisation issues continue to hamper commercialisation [17]. ALCA yields range significantly (10-80 per cent GHG reduction) with cultivation system, energy source used to harvest it and assumptions on the co-product valorisation [23].

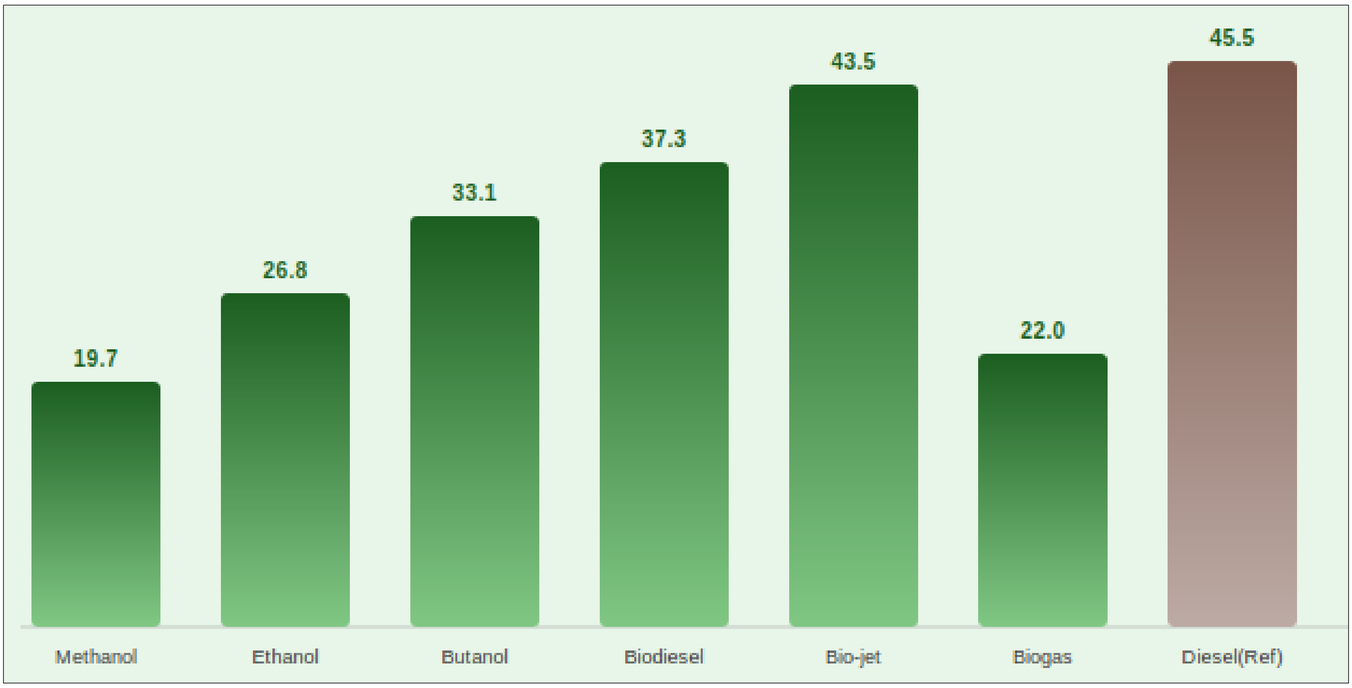

Fig 7: Energy density of various biofuel types

7.2 Techno-economic assessment

The price of production of biofuels is a very important factor that can be used to determine the competitiveness of the market against petroleum-derived fuels. In India, sugarcane ethanol is first-generation at about 43 50 Indian Rupees per litre (0.52= 0.60 USD/L), which is competitive compared to petrol at taxation rates at present [8]. The second-generation cellulosic ethanol costs are very high at 60-80 Rupee per litre because of high pretreatment cost and enzyme costs, but falling enzyme costs and process optimisation is continuously reducing the gap [10]. The current costs of production of algal biodiesel are in the range of 200 to 400 Rupees per litre at pilot scale, which is much higher than economically viable ranges, but the estimates indicate that with large-scale deployment of photobioreactors and integrated biorefinery architectures, costs of algal biodiesel will be below 80 Rupees per litre [24].

Table 7: Techno-economic comparison of biofuel production in India

Biofuel Type	Cost (₹/L)	GHG Reduction	Energy Ratio	Maturity Level	Key Challenge
Sugarcane ethanol (1G)	43–50	60–80%	8:1 – 10:1	Commercial	Seasonal feedstock supply
Grain ethanol (1G)	52–62	20–40%	1.5:1 – 2:1	Commercial	Food-fuel competition
Cellulosic ethanol (2G)	60–80	80–95%	5:1 – 8:1	Demo/Early comm.	Enzyme costs, pretreatment
Biodiesel – Jatropha	55–70	50–65%	3:1 – 5:1	Commercial	Low plantation yields
Biodiesel – UCO	48–58	70–85%	4:1 – 6:1	Commercial	UCO collection logistics
Algal biodiesel (3G)	200–400	10–80%	0.5:1 – 3:1	Pilot	Harvesting energy cost
Biogas (CBG)	35–45	55–75%	3:1 – 5:1	Commercial	Feedstock aggregation
Bio-jet fuel (SAF)	120–180	50–70%	2:1 – 4:1	Demonstration	High processing cost
Engineered biofuel (4G)	>300	>90% (proj.)	TBD	Laboratory	Regulatory, biosafety

8. Integrated biorefinery concepts

The integrated biorefinery paradigm is a paradigmatic shift in the process of producing biofuels that resembles the petrochemical refinery paradigm that adopts the transformation of biomass into a continuum of fuels, chemicals, material and energy products to achieve maximum value recovery of all the feedstock components [29]. This type of systems-level solution has a dramatic positive impact on the economic viability and environmental sustainability of biofuel production, by removing the waste streams, and creating high-value co-products that cross-subsidise the cost of fuel production.

Lignocellulosic Biorefinery Models Lignocellulosic biorefinery models provide a durable solution to bioethanol challenges in the United States.

8.1 Lignocellulosic biorefinery models

Lignocellulosic biorefinery models are a lasting solution to bioethanol issues in the US.

The cellulose fraction is hydrolysed and fermented into ethanol or butanol, the hemicellulose-derived xylose can be used to make xylitol (useful food additive) or furfural (platform chemical), and the lignin can be converted into phenolic resins, carbon fibres or even burnt to generate combined heat and power (CHP) [17]. In a zero-waste biorefinery setup, Indian scientists at the National Institute of Interdisciplinary Science and Technology (NIIST), Thiruvananthapuram, have shown that coconut husk biomass can be simultaneously converted to bioethanol, nanocellulose and activated carbon [18].

8.2 Algal biorefinery integration

Algal biorefineries ensure highest revenue is realised through high value product extraction before converting them to fuels. The de-oiled algal biomass (high in proteins and carbohydrates) left after lipid extraction to produce biodiesel can be used to make animal feeds, anaerobic digestion into biogas, or provide fermentable sugars to produce ethanol [22]. The high-value pigments, including astaxanthin (Hematococcus pluvialis), phycocyanin (Spirulina platensis), and beta-carotene (Dunaliella salina) fetch prices in the market ranging between 2,500 and 7,000 USD per kilogram, which is sufficient to co-produce biofuels at a lower cost [24].

Fig 8: future bioenergy potential across sectors

9. Challenges and Future directions

Although the technology has advanced immensely, widespread implementation of botanical biofuels is not possible because of a number of interrelated issues in the areas of technical challenges, economic challenges, logistical challenges, as well as regulatory challenges [29].

9.1 Technical challenges

The one most important technical limitation to the second-generation biofuel being cost-effective is the lignocellulosic biomass recalcitrance. It has a crystalline structure, which resists enzymatic degradation, cross-linking by hemicellulose and encasing within the lignin matrix, which adds up to 2030 per cent of the overall production costs [17]. In the case of algal biofuels, harvesting (centrifugation, flocculation, or filtration of dilute suspensions at 0.5-5 grams per litre) and cell disruption processes consume 20-40 per cent of the total energy content of the extracted lipids, which is highly detrimental to net energy balance [22]. The control of contamination of open cultivation systems, genetic stability of modified strains during long cultivation periods, and the establishment of strong lipid extraction protocols that can be employed with wet biomass processing is another technical contact point that needs to be solved [23].

9.2 Economic and Logistical problems

Diffuse and seasonal distribution of agricultural biomass poses large logistical problems to feedstock aggregation, transportation, and storage. The economically viable biomass collection radius in India of 50-80 kilometres of the processing facility, limits the scale of a plant and the throughput [10]. The enzyme expenses of lignocellulosic hydrolysis, although decreasing as a result of expenses going down to about 50 US cents per gallon of ethanol in 2010 to less than 15 cents by 2024 represent a significant portion of the production costs [19]. Second generation biorefineries (capital investment of 150-250 million USD in a 100 million litre/per year plant) are not easily financed and especially in the developing economies [20].

9.3 Future research priorities

The way forward in future research lies in the consolidation of bioprocessing organisms that can concomitantly saccharify and ferment lignocellulosic feedstock and simplify the process and minimize capital demands [5]. Synthetic biology developments offer designer microorganisms in response to specific feedstock mixtures, as well as fuel specifications. The use of artificial intelligence and machine learning to optimise cultivation conditions, anticipate biomass production, and formulate new cocktails of enzymes is another new interdisciplinary interface [26]. In India, a pioneer case of using biofuel production and concurrently moving towards producing renewable energy in the rural agricultural cluster on a decentralised basis (solar-powered bio-refineries) provides an innovative approach to ensuring energy access, waste management, and rural livelihood improvement [9].

10. Conclusion

Using plant power with new technologies of biofuels is a radical means of achieving sustainable energy security especially to the agrarian economies like India. This review paper has shown that botanical biofuels have evolved overtime since first generation food-crop-based systems to more advanced fourth-generation engineered systems that involve synthetic biology and carbon capture technologies. The philosophy of aggressiveness in Indian policies, biomass resources, and increasing research capacity make India a possible world leader in bioenergy innovation. Nevertheless, to achieve this potential requires a long-term commitment to research and development, the development of a strong supply chain network to aggregate feedstock, the further decrease in enzyme and processing prices and the establishment of favourable regulatory mechanisms that do not undermine biosafety but facilitate innovation. The integrated biorefinery concept, which relates fuel generation with high-value byproducts, comes out as the most cost effective paradigm in increasing botanical biofuels to commercially significant scale.

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