



Biomass to bio-energy supply chain: Economic viability, case studies, challenges and policy implications in India

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ABSTRACT

Biomass supply chain (BSC) management is an integral part of renewable energy projects, which include biomass-harvesting, collection, storage, processing and transportation to the bio-energy plants. The sustainability concept identifies economy, environment, and society as the three principal pillars of bioenergy. With an effective BSC implemented, all three dimensions of sustainability can be attained. Although, there's been extensive research on the environmental sustainability of BSC, the economic aspects are under-represented in existing literature. So, an elaborate analysis on the economic viability of BSCs developed worldwide and those in India is critical, and needs to be studied. This review conducts a detailed accounting of the economic aspects of a BSC which includes the existing challenges in designing an environmental-cum-economically efficient BSC and strategies to address the issues. The Indian context has been studied on the BSC models, highlighting their shortcomings, while encapsulating the essential insights from global BSC models for a cost-effective BSC-to-bioenergy in India. This review also emphasizes the policies supporting the BSC in India and forecasts the future biomass demand and supply. This review will provide stakeholders with critical insights on BSC and related challenges and assist them to investigate and devise strategies for successful implementation of BSCs in India.

Introduction

Current state of bioenergy in India

Bioenergy is the largest source for renewable energy production and the associated demand is expected to increase as national climate change mitigation strategies look towards sustainable and low-carbon

energy alternatives. As per the 2023 International Energy Agency (IEA) report, 55 % of the total renewable energy, and 6 % of the total energy source across the world is derived from bioenergy. IEA's Net Zero Emissions (NZE) scenario by 2050 expects to see a rapid increase in bioenergy usage, capable of displacing fossil fuels by 2030. India has a strong agricultural and allied sector that contributes significantly to the country's GDP (~20 %) and is also the largest source of livelihood (>50

Abbreviations: BSC, Biomass Supply Chain; NZE, Net Zero Emissions; GDP, Gross Domestic Product; MMT, million Metric Ton; MoP, Ministry of Power; NPV, Net Present Value; SC, Supply Chain; GHG, Green House Gas; FPO, Farmer Producer Organizations; MSP, Minimum Support Price; CMRA, Custom Milled Rice Agency; RI, Resource Institutions; MIS, Management Information System; CRR, Crop-to-Residue Ratio; FRP, Fair and Remunerative Price; NGO, Non-governmental organization; IoT, Internet of Things; RL, Reinforcement Learning; AI/ML, Artificial Intelligence/Machine Learning; CSR, Corporate Social Responsibility; AHP, Analytical Hierarchy Process; GIS, Geographical Information System; PNFA, Process Network Flow Analysis; CYN, Chinese Yuan; CSS, Centralized storage sites; FRCS, Forest Reduction Cost Simulator; GT, Green Ton; MLP, Multi-objective Linear Programming; CFA, Central Financial Assistance; MNRE, Ministry of New and Renewable Energy; MoPNG, Ministry of Petroleum; MTHP, metric ton per hour; SBMG, Swachh Bharat Mission-Gramin; 1G, First generation; 2G, Second generation; 3G, Third generation; MSW, Municipal Solid Waste; OMC, Oil Marketing Organization; CBG, Compressed Biogas; CBO, CBG Blending Obligation; LNG, Liquefied Natural Gas; CNG, Compressed Natural Gas; PNG, Piped Natural Gas; BAM, Biomass Aggregation Machinery; CBP, Ethanol Blending Petrol; CGD, City Gas Distribution; DPI, Development of Pipeline Infrastructure; MDA, Market Development Assistance; FOM, Fermented Organic Manure; LFOM, Liquefied Fermented Organic Manure; PROM, Phosphate Rich Organic Manure; IEA, International Energy Agency; Twh, Terawatt hour; BDO, Block Development Officer.

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% of the population. This presents a large and widespread biomass availability to the country. Being renewable and carbon-neutral, biomass poses the potential to provide livelihood to humankind [1]. The National Biomass Atlas of India reports that India has an annual agricultural residual biomass generation of ~750 million Metric Tons (MMT) of which 230 MMT remains surplus every year having a biomass power potential of about 28 GW (National Biomass Atlas, SSS-NIBE. As per Central Electricity Authority, Ministry of Power (MoP) currently 41.4 % of total energy supplied in India is derived from the renewable sources, of which 2.5 % is from biomass. The total installed renewable energy capacity of India is 180 GW (including large hydropower: 10 GW being contributed by biomass (Ministry of New and Renewable Energy, GoI. For adequate production and utilization of bio-energy, the flow of biomass from its production phase to its transformation phase has to be optimally designed for the development of a cost effective and efficient biomass supply chain (BSC).

Research gaps

A biorefinery demands a reliable, cost-effective and perennial feedstock supply. It's crucial for any biorefinery installment that an efficient BSC and its management is developed so that an economically viable biofuel pricing is facilitated. However, the biorefinery project also needs to deal with an investment risk which can be offset by assessing storage, handling and transportation of biomass. Weather and seasonal uncertainties, deviation in characteristics (physical/chemical, non-uniform distribution of biomass geographically, local and national biomass logistics and bio-energy distribution infrastructure and varying governmental policies are some of the many factors which affect the economic feasibility of any BSC [2,3]. The price of the final biofuel and the approximate returns to feedstock suppliers, along with the effect of the combination of volume and price of different products on the farm and income per unit hectare, need to be assessed [4]. A BSC needs to be integrated with private sector investment so as to achieve clean energy. This would require the development of strong supply chains (SC) which can ensure a long-term sustained supply of biomass to power plants and the private sector [5]. This would also help to streamline the price of biomass in the market. Literature has proposed BSC models addressing various biomass feedstocks. However, there is less discourse regarding the economic feasibility analysis of BSC, which frequently underlies the failure of bioenergy initiatives. Further, the existing papers haven't deeply discussed the existing BSCs in India and their viability on the economic front. They also lack on detailed discussions on latest policies on biomass and its SC in the Indian context. [69] indicated in their review that the predominant keywords used by researchers investigating developing concerns in the field of BSC were primarily focused on the forest biomass, pretreatment, processing, location, carbon footprint, uncertainty, strategic and tactical planning, and integrated SC. This suggests that the economic viability was not the major concerns of a BSC design. Therefore, while bio-energy has significant potential for energy generation and livelihood creation in India, a key bottleneck for the growth of the bio-energy sector lies in the development of reliable BSCs in India. It's imperative that, prior to deciding on investment in bio-energy sector, stakeholders perform a comprehensive feasibility study for both technology and BSC aspect. Thus, to address these gaps, the present review highlights the economic aspects of the BSC models developed worldwide, the key takeaways therefrom, the challenges on BSC faced in India, the economic feasibility of the BSC models in India. Being an emerging sector, bioenergy has developed a recent renewed interest several policies that have been launched in last three years which can support the sector. Insufficient information prevents stakeholders from capitalizing on support and safeguarding themselves during the design, initiation, and stabilization phases of bioenergy initiatives. The review also highlights the government policies that have been developed to enhance the bio-energy production. The authors underline the possible solutions which would help the stakeholders and

policy makers to develop effective BSCs in India. The uniqueness of this review lies in a detailed discussion focusing only on economic aspects of developing a BSC in India. This comprises of identifying the vulnerability that a BSC faces during its design and execution phase, if the economic considerations are not paid equal heed as the environmental aspects. Thereafter, the India-specific characteristics of a BSC and the associated challenges are discussed followed by a detailed assessment of the major takeaways from the case-studies of the global BSCs. As policy implications play an important role in allocating the annual budget to a bioenergy program and the rate of finance distribution for every biomass-to-bioenergy component by individual ministries, a detailed yet comprehensive review section is dedicated to the bio-energy policies aiding in BSC development in India. The estimated demand and supply of biomass in India has been projected which would not only give a first-hand knowledge on the ongoing demand-supply relation of the surplus biomass, but would also help in mapping the future biomass requirements for designing a cost-effective BSC. This analysis will provide an alternative perspective for BSC modelers, research analysts, policy-makers, entrepreneurs, and stakeholders to develop an economically viable BSC.

Review methodology

The current study employed a systematic approach to locate, identify, and select published literature for review. The content analysis integrated quantitative and qualitative elements to examine both structural and content dimensions. The literature review was commenced by using the search engine of Scopus by entering the most appropriate keywords relevant to the study. With the keywords search "Biomass" AND "supply chain", 3086 articles were found by the search engine. However, the uniqueness of the study was determined by the fact that the search engine found only 57 articles with the keywords "Biomass" AND "supply chain" AND "India"; whereas when the search was refined by using the keywords "Biomass" AND "supply chain" AND "economics" AND "India", only 5 articles were screened. This implies that there was quite limited research that covered the economics of BSCs in India, making this review a novel review study based on the economic viability of BSCs in India.

Thereafter, literature was downloaded with different keywords to cover different aspects of a BSC in India. First articles were screened related to the basics of BSC between 2010 and the present with keywords 'Biomass supply chain', 'Biomass supply chain management India', 'Case studies biomass supply chain economics India'. Second, we refined the publication timeframe to include 2016 to the present with keywords 'economics of biomass supply chain', 'case studies biomass supply chain economics', 'biomass supply chain economics India', 'challenges biomass supply chain economy'. Only those papers were retained which had discussions or investigations of the economic viability of the BSC. The network visualization and density visualization maps were created in VOS viewer therefrom (Fig. 1(a), (b)). In the network visualization, items are depicted by their label and, by default, also by a circle. The dimensions of the label and the circle of an item are dictated by the object's weight. As the weight of an item increases, so does the size of its label and circle. In our review process (Fig. 1(a)) the word 'location' had the maximum weightage, followed by an equal weightage of the words: 'tool', 'strategy', 'concept', 'economy', 'information', 'pathway', 'economic viability'. This implies that the most repeated term in the literature collected for the review was 'location', followed by an equal occurrence of the words listed above. Density visualizations offer an easy summary of the primary regions within a bibliometric network. The greater the quantity of objects in the vicinity of a point and the higher the weights of these nearby items, the closer the point's hue approaches yellow. The inverse relationship indicates that a reduced quantity of items in the vicinity of a point, together with diminished weights of the nearby items, correlates with the point's hue approaching blue. In Fig. 1(b), it's observed that the region around the

terms 'supply chain', 'tool', 'pathway', 'location', 'optimal solution', 'renewable energy source', 'circular economy' is primarily yellow as compared to the other regions in the picture. This implies that these points have a greater quantity of objects in their vicinity, rendering a high weightage of these terms in the literature. Network visualization and density visualization are essential maps created after the literature gathering process and are highly beneficial throughout a review.

Biomass supply chain (BSC)

Components of a BSC

Biomass crops consist of three generations of cropping components: first-generation biomass crops are directly edible in its own form (canes and corns, second-generation biomass is the non-edible parts of plants (stem, husk, leaves, and the third-generation consist of algae [6]. The share of bio-energy derived from biomass is expected to increase as national climate change mitigation strategies look towards sustainable and low-carbon energy alternatives. A BSC model needs to be designed on objective functions, foremost being minimization of overall cost followed by maximization of the overall profit [7,8]. Additionally, some researchers have maximized the net present value (NPV while designing a BSC [9,10]. A BSC encompasses activities like biomass-harvesting, collection of harvested biomass, storage, pre-treatment, and transportation/logistics to the bio-energy plants [6]. Harvesting of biomass is carried out in areas of biomass availability, such as farmlands, forests, lumbermills, and furniture manufacturing points. The limited availability window for collection of crop residues calls out for an increasing cost of equipment, resources and skilled workforce. Post-harvesting, the collection of biomasses for further processing and storage is done by various techniques such as chopping (shredding the biomass to reduce its particle size, baling (compacting the biomass into cylindrical/rectangular shaped bales) and loafing (arranging the biomass with respect to its size to achieve least packaging space. Pre-processing of biomass is done to densify the biomass without decreasing its calorific value, and to reduce the transportation cost [6]. Subsequently, if the end-user operates throughout the year, storage of biomass necessitates the availability of temperature-based controller for its preservation. Transportation of biomass from its site of harvesting to fuel processing can be done by roads, railways and waterways. Since biomass is a low-density raw material, the critical factor governing the capacity of transportation is the volume of biomass, instead of its weight. This increases the total cost for transportation, handling and storing the biomass, thus increasing the overall cost of the BSC [11]. Therefore, it is essential to develop a BSC that ensures environmental sustainability while maintaining economic viability. An overview of various components of a BSC whose optimization can adhere to the development of an economic BSC in India (Table 1.

Economic problems faced in a BSC

The BSC for biofuel production presents many cross-cutting processes where technology and human capital, transportation and logistics, policies, governance, and institutional mechanisms are identified as the major ones. These challenges apply to both first- and second-generation biofuels. Despite extensive research and development on biomass-to-bio-energy conversion technologies (e.g., pyrolysis, gasification, liquefaction, hydro-processing, and catalytic conversion, the SC remains vulnerable due to biomass availability, costs and seasonality, technological inaccessibility, and uncertainties due to market fluctuations. The majority of conversion technologies in the market are imported from other countries, resulting in high costs and matured resources for developing the technology [12]. However, BSC reliability has remained an issue for biofuel production [13]. This is because that the quantity of biomass generation fluctuates based on crop output, seasonal variation, short window period for residue harvesting, coal-

Table 1
Characteristics of different components of a BSC.

BSC component	Different mechanism of each component	Characteristics of the mechanism
Harvesting and collection	Biomass from forest	<ul style="list-style-type: none"> While some plantations are dedicatedly energy crops, others are residues from the forest industry and sawmills. There also exists some biomass which are harvest residues inappropriate for usage in the wood and timber industry
	Harvesting forestry residues	<ul style="list-style-type: none"> Timber harvesting often consists of foliage and small branches which can be collected to be used as biomass fuel. Thinning process, whereby, some trees are cut down to enable other trees' diameter growth, also generate residues which can be used for the production of energy generation.
	Tree felling systems	<ul style="list-style-type: none"> Mechanized felling of trees include: in cut-to length system and tree length system. The in cut-to-length system involves cutting of 2-4 m logs of trees (branches removed), kept over in the forest, either spread out or arranged in piles. The slash, for energy production, is left in the forest to enable sun drying before collection. Chipping of the slash and collection of the forest residue is done only prior to usage for energy generation. Tree length system involves carrying the forest residue away from the forest immediately after harvesting them
	Medium to small scale	<ul style="list-style-type: none"> Harvesting of wood is done which is then collected: for firewood, or for sale These sustainably managed forests are the ones where handheld, mechanized saws are used for harvesting.
	Agricultural crop residues	<ul style="list-style-type: none"> This is done in areas which are easily accessible, where harvesting processes are integrated in the forest itself Timeframe for harvesting is limited and dependent upon the weather conditions
	Balers	<ul style="list-style-type: none"> When grains are harvested, the residues are left on the fields which are collected by windrowers. The residues are then converted to bales which can be of round, cylindrical, square or rectangular shape Energy crops are also converted to bales simultaneously after collection by the windrowers
	Forage harvesters	<ul style="list-style-type: none"> The plants are collected and directly loaded in trucks, leading to size reduction which prevents further shredding/grinding process
	Mobile pelletizers	<ul style="list-style-type: none"> They are moving pelletizers attached to trucks/tractors which eliminates the need of standard harvesting machines The reduces the cost of moving the bales to the pellet plants

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Table 1 (continued)

BSC component	Different mechanism of each component	Characteristics of the mechanism	
Pretreatment	Drying	<ul style="list-style-type: none"> Facilitates in storage and transportation of biomass Compliance with the specification of the bio-energy conversion technology Contributes to higher efficiency and reduced emission Passive drying- natural process of drying in the forests/agricultural lands without the application of external energy For gasification, pyrolysis and pelletization, active drying, i.e., use of external energy for excess heat is required Hot gases from burners are used to pass through a mixing chamber with perforated floor in a closed loop system 	
		Densification	<ul style="list-style-type: none"> Increasing of energy density and volume reduction helps in efficient logistics and storage in the BSC A homogeneous fuel which complies with heat and power generation technology standards
			Pelletization and briquetting
		Torrefaction	
			Pyrolysis and hydrothermal upgradation
Storage and handling	Storage size	<ul style="list-style-type: none"> Optimization of the size of storage area is vital in a BSC Larger storage units are preferred as it enables purchasing larger quantities of biomass at once, rendering lower price per unit of the feedstock Helps in flexible delivery schedules of the biomass 	
		Ventilation	<ul style="list-style-type: none"> To prevent condensation, moulding, inhalation of the hazardous spores and to allow drying and minimization of decomposition of biomass, sufficient ventilation is required Formation of carbon monoxide production is also prevented
	Drainage		<ul style="list-style-type: none"> Whenever water enters into the storage area, drainage has to be incorporated Difficult to incorporate drainage in underground storage areas, often leading to costlier BSC
		Wet biomass	<ul style="list-style-type: none"> Storage of liquid biofuels and animal slurries in tanks enables them to be pumped in pipelines

Table 1 (continued)

BSC component	Different mechanism of each component	Characteristics of the mechanism	
Transportation and Handling	Tipper trailer or truck	<ul style="list-style-type: none"> It's important to consider the time period for the storage of biomass without affecting the quality of the biomass This would help in long-term storage of the biomass Used worldwide for wood chips, pellets and forest/agricultural by-products Simplifies the offloading process, prevents the handling and additional equipment in the BSC 	
		Flatbed trailer	<ul style="list-style-type: none"> Suitable for palletized bag pellets, bales and logs It's an enclosed tank which can transport liquid biofuels/slurries and solid pellets The tanks can be connected with pipes in the delivery sites, enabling a clean delivered fuel
	Tanker, grain/ animal feed vehicle		<ul style="list-style-type: none"> Timber haulage is done by special lorries for timber industry Includes a crane for loading and unloading
			Timber haulage wagon
	Walking floor trailer	<ul style="list-style-type: none"> Same vehicle used for both chipping and transportation Useful for forest fuel handling For large scale powerplants with combustion/co-firing, the railway transportation is required 	
Chipper truck		<ul style="list-style-type: none"> Inland waterways, although slow, are low on carbon emissions Ships are used for transportation for non-time sensitive and long-distance transportation of large-scale biomass; carbon emissions per kilometre are one-tenth of the road transportation 	
		Rails/inland waterways/ship	

price impact on biomass-price, availability of harvesting machinery, road and vehicle infrastructure [14]. To guarantee the continuous functioning of biofuel production, several feedstocks as raw materials need to be considered. Conversely, this suggestion increases the technological obstacles associated with pre-treating and processing several feedstock types, each of which has its own distinct qualities and features [15]. While there are many advantages to using biomass for ethanol and bio-energy, such as its ability to promote agricultural growth, energy security, and greenhouse gas abatement, the conversion technologies and supply logistics provide significant obstacles to its adoption [16]. With decisions made at both the upstream and downstream sides, the BSC is a complicated system. Decisions have an impact on later SC operations [67]. Optimization models assess the viability of using biomass for bio-energy/biofuel and enable decision-making at multiple levels. The examined research mostly focused on biomass/ bio refinery location, management of stocks, and manufacturing planning. Frequently used numerical performance measures include cost minimization and profit maximization. The BSC configuration is complicated due to several elements affecting the system. A comprehensive logistical analysis is necessary to achieve productive manufacturing of biofuel [17]. Reducing the costs associated with harvesting, shipping, and production should be the primary goal of second-generation biofuel projects, according to numerous SC modelling and optimization studies [18]. Several studies show that lowering harvesting, shipping, and manufacturing costs can enhance project economic viability. A number

of studies lack a consistent cost-optimization approach for second generation bio-energy logistics [19]. However, SC logistics might become more challenging with an increase in the second-generation biofuel production and a growth in competition for biomass feedstocks [20].

Several researchers modelled and optimized SC logistics for various biomass feedstocks to reduce costs and transportation to plants [15]. In the past, modelling has been successfully applied by the mineral oil and chemical industries for plant construction and strategic planning of the SC [15]. Linear and mixed integer programming models are widely employed in research [15]; while hybrid and stochastic models [21] have examined several SC solutions for second generation feedstocks. [22] examined the economic and environmental sustainability of centralized versus decentralized biomass collection in mobile pyrolysis units. A comparative analysis of pyrolysis with alternative technology possibilities, including fuel upgrading and energy production was performed. On analysis of switchgrass particle size data to determine moisture and ash content, it was observed that high moisture and ash levels had a negative impact on unit delivery costs. Also, poor biomass quality leads to higher costs for quality management. The Idaho National Laboratory reports that standard models disregard feedstock quality constraints, resulting in lower logistical costs [23]. Using a conventional linear programming model the study included the quantification of moisture percentage as a motivating factor for cost optimization [18]. The model examined how moisture percentage and vehicle designs affect SC costs and material distribution. It highlights the importance of controlling moisture when planning logistics for biomass supply networks. The research offers a significant understanding of when and how much biomass should be harvested, which forest zones should be harvested and how long to store the biomass along the side of the road. The economy of a BSC depends on factors including cultivation, harvesting, technology, personnel, raw material costs, transportation, and conversion processes [24]. Bio-energy industry faces numerous cross-cutting challenges, the most significant of which is financial viability of BSC. Switching from an economy based on fossil fuel to one based on biofuels would be one method to lessen the adverse effects of climatic change. The creation of bio-based SCs, which diverge greatly from traditional SCs, is necessary for this replacement [25].

By creating an economic life cycle assessment model, one may have a better understanding of the economic cost of BSC [5]. Another hurdle to BSC is the low return on investment cost, and offered a multiple objective oriented optimization approach where yearly cost may be analyzed simultaneously [5]. Quantifying economic and environmental sustainability requires considering greenhouse gas (GHG emissions and transportation-related costs associated with biomass. Doing a thorough techno-economic study is necessary to spark industry participants interest in and encourage more investment in biomass-based businesses. Furthermore, in order to produce a more accurate and trustworthy feasibility estimate, the assessment must account for a number of SC variables, including the attainability of biomass, demand variation, and material price fluctuations [26].

BSC management in India: Characteristics and challenges

Characteristics of BSC models developed in India

Biomass is widely utilized in a variety of rural and conventional businesses [27]. Advanced biomass utilization leverages the benefits of contemporary biomass conversion technologies to produce bio-energy and biofuels. Table 2 depicts various BSC models developed in India and the key features which would help in enhancing the economic sustainability of the BSC. Additionally, various technological solutions for the utilization of surplus biomass for bio-energy production have been tabulated in Table 3.

Table 2
Summary of the BSC models developed in India.

Biomass/ biomass supply chain	Key features	Effect on the BSC	References
Paddy procurement process by Farm Producer Organizations (FPO), West Bengal	<ul style="list-style-type: none"> The Food and Supplies Department included the Farm Producer Organizations (FPOs) to procure paddy from the farmers at Minimum Support Price (MSP) through its Custom Milled Rice Agency (CMRA) A triparty agreement had to be made between the FPOs, CMRA and the authorized Rice Mill The Resource Institutions (RIs), which are the stakeholders in this case, facilitated the SC by providing with the list of FPOs, address, bank details, the contact of the authorized person of the FPO to the CMRA and to the Department of Food and Supplies. The RIs maintained the Management Information System (MIS) of the transactions of the paddy procurement by all the FPOs. The RIs were also responsible for sharing the information with the Government department and to monitor the timely payment to the farmers. 	<ul style="list-style-type: none"> After this facilitation for the MSPs by the RI, the farmers are getting an additional benefit of 15 % per quintal of rice, over the market price. 	[66]
Biomass/ Sugarcane bagasse fuel energy and pricing by Maharashtra Electricity Regulatory Committee	<ul style="list-style-type: none"> Secondary data collection involves- historic data collection of district-wise biomass collection, crop-to-reside ratio (CRR) of different biomass/bagasse, estimation of calorific value Primary survey and stakeholders' meeting- preparation of questionnaire, visit to biomass industries, farmers, aggregators, traders, and power 	<ul style="list-style-type: none"> Assessment of profit/loss in the sugar industry business- sugar business, co-generation, distillery-spirit and ethanol Consistency in the Fair and Remunerative Price (FRP) of sugarcane The transportation cost per ton of sugarcane to the power plant remains constant within specific 	[57]

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Table 2 (continued)

Biomass/ biomass supply chain	Key features	Effect on the BSC	References
	<p>plant owners in the command area, assessment of bio-energy potential of the biomass, biomass pricing, seasonal availability.</p> <ul style="list-style-type: none"> Data analysis and reporting- Estimating the excess amount of biomass feedstock, its availability during different seasons, SC logistics, fuel pricing, and availability: along with the top five states in India, validate data from primary field surveys and secondary sources, determine the ultimate cost of gasoline and its availability, taking into account all aspects like collection, processing, transportation, and storage costs 	<p>distance ranges, such as 0 to 50 km and 50 to 75 km.</p> <ul style="list-style-type: none"> The cost of sugarcane is determined based on the FRP set by the government, with the deduction of expenses related to harvesting and transportation from the FRP. 	
Surya Chambal Power Limited, Rajasthan	<ul style="list-style-type: none"> A 7.5 MW capacity mustard-husk based in Kota district of Rajasthan Suffered from the problem of stubble burning due to lack of monetary resources A mechanized system of solving it were found by the farmers of the company The farmers installed special plates in the harvesting machines, so that the plant remains be removed from the lower side of the plant and least part of the plant is wasted. Never used conventional sources of power to grow biomass Annually purchases biomass worth ₹10–12 Cr (1.1. to 1.4 million USD) 	<ul style="list-style-type: none"> Least wastage of biomass Improved mechanization Generates adequate income for the farmers 	[58]
Paddy BSC challenge in Punjab	<ul style="list-style-type: none"> Punjab, as an agrarian state, generates an annual biomass of 18–20 MMT from 	<ul style="list-style-type: none"> Thus, the Punjab state government has developed measures for ex- 	Based on the discussions of the authors with stakeholders

Table 2 (continued)

Biomass/ biomass supply chain	Key features	Effect on the BSC	References
	<p>paddy, with a collection period of roughly 35–40 days.</p> <ul style="list-style-type: none"> The characteristics of paddy biomass: high silica content, alkaline earth metals, low bulk density, and light texture renders the shredding and grinding processes complicated, resulting in significant machinery wear and tear. The issues associated with paddy straw in thermal power plants encompass furnace slagging, superheater tube fouling, and ash disposal; in CBG facilities: economic feasibility and management of FOM; in bioethanol plants: advancement of technology during the stabilization phase. The Gross Calorific Value of paddy biomass is approximately 3000–3500 kcal/kg, rendering it a viable alternative to fossil fuels for power generation. 	<p>situ management of paddy straw.</p> <ul style="list-style-type: none"> The state is the first to announce a mandate requiring the substitution of at least 20 % of coal with paddy straw-based pellets in brick kilns. Therefore, despite the issues related to paddy straw in its processing to bio-energy, state government policies can aid in its effective utilization to develop a sustainable SC. 	
2G Ethanol plant, Panipat Biomass Supply Model	<ul style="list-style-type: none"> The aggregation, transportation, unloading, and stacking of paddy straw is conducted by the Government of Haryana (GoH) via FPOs, Custom Hiring Centers (CHCs), and Baler Farmers. Depot operations and subsequent management are handled by the Indian Oil Corporation Limited (IOCL). A committee comprising members from GoH and IOCL, chaired by the Deputy Commissioner of district Karnal, has been established to determine the procurement price 	<ul style="list-style-type: none"> The GoH organizes the allocation of land for biomass depots; processors receive a biomass incentive of Rs 1000 per ton of paddy straw; biomass is gathered from clusters located within a 50 km and 100 km radius of the plant. Assistance from the agriculture ministry and state government is essential for operating the plant at full capacity, including a dedicated ex-situ crop management program. 	Based on discussion of authors with stakeholder

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Table 2 (continued)

Biomass/ biomass supply chain	Key features	Effect on the BSC	References
	of paddy straw from FPOs and CHCs.	<ul style="list-style-type: none"> Other kind of support from the state government includes provision of credit lines for FPOs, VLEs, CHCs, and individual farmers from banks at minimal interest rates for the acquisition of biomass aggregation farm equipment and working capital; establishment of biomass pricing analogous to crop MSP; and identification of specialized biomass clusters 	
Thermax Onsite Energy Solutions Limited	<ul style="list-style-type: none"> Its unique business model enables the BSCs to focus on the bio-energy production process, rather than other nodes of the SC Started a a strategic backward integration initiative Has established in captive biomass briquetting units in Karnataka and Maharashtra with a production capacity of more than 4000 tons per month Has provided a sustainable supply of biomass designed boilers based on multiple biomass Entered into long term contract with the biomass fuel suppliers 	<ul style="list-style-type: none"> Has deployed trained manpower Has set up labs at every site for fuel and water testing Established high end automated controls, online and remote monitoring and robust MIS practices 	[73]
Unmukt Urja Pvt. Ltd.	<ul style="list-style-type: none"> Collaborates with the farmers and the agricultural communities Uses its unique sourcing and aggregation model to source the biomass Integrates it through a mobile application named SAATHI Has partnered with a non-governmental organization (NGO) 'sampurn Krishi Utthan 	<ul style="list-style-type: none"> SAATHI app helps them reduce the cost of biomass aggregation and transportation SC of straw, with emphasis on reducing the transportation cost of the same 	[74]

Table 2 (continued)

Biomass/ biomass supply chain	Key features	Effect on the BSC	References
Punjab Renewable Energy Systems Private Limited	<ul style="list-style-type: none"> A unique business model- They first enter into a long-term agreement with the clients at a pre-decided price and ensure a regular supply of biomass at desirable quantity and appropriate quality. Simultaneously, they provide additional revenue to the farmers by purchasing the biomass from them, which would have otherwise been burnt in the agricultural fields. 	<ul style="list-style-type: none"> Aims to provide employment to the local farmers and the youth. Additional source of income to the farmers 	[68]
Biofuel Circle	<ul style="list-style-type: none"> Provides BSC services through its digital cloud-based platform to develop a SC to power the biofuel/ bio-energy plants Developed a Biomass Bank model whereby it purchases biomass directly from the farmers, rents the machinery to farmers, helps the client schedule and track the biomass transported to them 	<ul style="list-style-type: none"> simplifies contracting by eliminating the hassle of vendor evaluation and negotiation with the suppliers looks after the farmers' online registration, biomass supply, a network of rural participants, payments and invoices as digitally carried out 	[75]
Praj Industries SC model for Second Generation Ethanol	<ul style="list-style-type: none"> The first model deals with supply of biomass locally by the farmers. The second-generation bio-ethanol firm may directly get biomass from farmers In the third model, bioethanol producing firm shall acquire biomass from the producing organizations, who may also have owners in the stakes. 	<ul style="list-style-type: none"> Reduction in biomass price by establishing long-term supply agreements directly with major farms Reduces the expenses of decentralizing infrastructure Regulated and constant supply of biomass to the plant The organization engages in commercial activities related to its primary goods or services, with the aim of benefiting its members. Producer groups facilitate more efficient purchasing and selling for farmers by 	[71]

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Table 2 (continued)

Biomass/ biomass supply chain	Key features	Effect on the BSC	References
		leveraging economies of scale and reducing transaction costs for both vendors and purchasers.	

Challenges to economic feasibility of BSC management in India

The BSC design should minimize operational costs and lower the fuel landing cost at the plant’s gate. Therefore, factors such as the quantity of net surplus biomass (crop type, season, location, volume), network flow (transported values), storage, and safety must be taken into account. Despite a number of models being developed in India, the economic sustainability is still a significant obstacle for the enhanced implementation of bio-energy and bio-fuels. Therefore, it is imperative to model and optimize the BSC for improved management applications that result in significantly lower costs and more effective logistical processes. The major problems in BSC that have been prevalent in India are described further in the sections that follow.

Data collection issues

An efficient BSC in India faces issue with lack of availability of credible data, rendering it difficult to acquire an updated data on for analysis. A strong agricultural sector of India contributes significantly to the country’s Gross Domestic Product (GDP) (~20 %) and is the largest source of livelihood (>50 % of the population) presenting a large and widespread biomass availability to the country. However, the means to access to the data is limited. Subsequently, the available data analysis in the country indicates variation in mapped data and actual available data. Additionally, the available data is static in nature, which does not capture regional variations in biomass characteristics. Moreover, most studies use limited time-span secondary source data, which lacks surplus residue fraction, crop residue ratio, and species variation and its effect on biomass generation within a crop. Thus, this incompetent data chain requires a constant work on updating of yearly data by regular survey programs, access to single department to work and deliver the specific data, and updated information to be provided to the other ministries on the availability of the new data. Additionally hiring of data scientists and on-field skilled manpower should be done frequently and largely, so that there is frequent analysis and quick rectifications of any errors that may occur.

Data acquisition

One of the major shortcomings in BSC rendering it cost-intensive is the problem with data acquisition. Indian BSC managers and stakeholders lack in the extensive usage of Advanced Data Analytics and Forecasting techniques (Fig. 2) which makes data acquisition slow. Demand planning which involves forecasting the biomass demand–supply scenario at different locations of the country and seasons of the year, segmentation of products based on biomass characteristics and demand requirement, providing decision making tools like reinforcement learning (RL), optimizing the BSC by genetic planning, chatbots for user-machine interaction for BSC information, digital-twin technology, blockchain technology and scheduling delivery and truck-load generation are all the solutions which can be provided by AI/ML (Artificial Intelligence/Machine Learning) to enhance and accelerate the BSC.

Smart Farming is a developing method in which field management chores are conducted using location and data, improved by context awareness and activated by real-time conditions [28]. BSC steps needs to

Table 3

Solutions for utilization of surplus biomass for bio-energy production.

Technology/ Schemes	Background	Applications and advantages
Paddy straw mulching	<ul style="list-style-type: none"> High organic nutrient from crops Need to be returned to soil to retain its fertility and yield potential 	Applications: <ol style="list-style-type: none"> Enhancing soil fertility Increasing the soil productivity over 3–4 years
<ul style="list-style-type: none"> Happy seeder + Super straw management Loose straw chopper + Happy seeder Stubble shaver + Happy seeder (with press wheels) Chopper + Wet mixing + No till drill 		
Pyrolysis	<ul style="list-style-type: none"> Biomass to biochar Burning in complete absence of air Organic content of the residue is converted to carbon in biochar, equivalent to activated carbon 	Applications: <ol style="list-style-type: none"> Soil conditioner Bio-remediation of degraded soil Char briquettes Value-added products like renewable incense sticks, de-odorize
Briquetting	<ul style="list-style-type: none"> Briquette is compressed biomass in 6:1 ratio Hydraulic press machines used for compressing 3-4’ long cylinders as briquettes Combustion generates low emissions 	Enablers in the BSC: <ol style="list-style-type: none"> Industries using briquettes need to be properly recognized Green certificates and rewards for those providing high quality briquettes
Pelletization	<ul style="list-style-type: none"> Compressed biomass in 6: ratio 20–40 mm long, 6–8 mm diameter Used in specially designed stoves in presence of optimum air 	Applications: <ol style="list-style-type: none"> Cooking stoves/heating applications in domestic and industrial scale Substitute for fossil-fuel based cooking Enablers: <ol style="list-style-type: none"> A service ecosystem can be enabled for maintenance of palletization machines Cook-stove subsidies for replacing wood/coal
Bio-CNG	<ul style="list-style-type: none"> Anaerobic digestion of organic biomass produces biogas ~ 60 % CH₄ CO₂ is stripped and the remaining gas is compressed to form bio-CNG 	Applications: <ol style="list-style-type: none"> Commercial-canteens, hotels, residential clusters Industrial- glass, cement, metal, textile Automotive- vehicles with CNG
Liquid fuels from biomass	<ul style="list-style-type: none"> Biomass condition- drying and sizing of biomass Hydro-oxygenation of volatilized biomass to produce raw hydrocarbon product Fixed-bed hydro treater- for removal of various contaminations from the hydrocarbon fuel Hydrogen manufacturing units- conversion of light gases which are generated in the first stage to renewable hydrogen 	Applications: <ol style="list-style-type: none"> Petrol and diesel for vehicles Enablers: <ol style="list-style-type: none"> Required infrastructure only in the form of road/rail transport Broad range of biomass can be used Low operational expenditure Monetizable Reduces carbon footprints

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Table 3 (continued)

Technology/ Schemes	Background	Applications and advantages
Support service-based shared infrastructure	<ul style="list-style-type: none"> The government can bring schemes for supporting entrepreneurs who look forward to owning the farm implements and providing service to the farmers at low cost Service aggregators serve as link between farmers and entrepreneurs The Block Development Officer (BDO) will consider the availability of implements, tractors, demand for the ex-situ/in-situ paddy cultivation area BDO will also check the quality and affordability of the services given to the farmers, provide training to the farmers and create awareness about the in-situ crop residue management 	Advantages: <ol style="list-style-type: none"> Awareness campaigns for farmers about the long-term benefits Exchange of best-practice amongst the farmers Farmers recognition
Process-based incentives for entrepreneurs	<ul style="list-style-type: none"> Provision of performance-based incentives to the entrepreneurs based on field area covered during two cropping seasons 	Advantages: <ol style="list-style-type: none"> Motivates the entrepreneurs for better asset utilization Offers in-situ soil incorporation services at affordable prices

be digitalized and made smarter to enhance its efficiency. Starting from residue collection, processing, storage, handling, and transportation remote information gathering, and data analyzing, is required till corrective actions can be adopted for the BSC optimization. This would facilitate optimized use of resources for easy handling of biomass at various stages of the BSC. Apart from managing the farming activities on-field, Smart Farming is involved in providing AI assistance to the analysts. When there is high involvement of machines in the SC, Big Data comes into picture which is a term given to large and complex data sets which can be mismanaged by the traditional data processing applications. Big Data necessitates advanced technology and analytical methodologies to extract important insights from its vast, fast-moving, and diverse data sets [29]. One approach to streamline Big Data is through

the implementation of the FAIR principle, which stands for Findable, Accessible, Interoperable, and Reusable. This philosophy aims to facilitate the straightforward retrieval and analysis of Big Data using analytical methods. [30] have described 'Data Chain' as a series of activities that starts with data collecting and ends with decision making and data marketing. It is a tool used for data analytics, consists of two layers: a technical layer that captures the raw data and converts it into information and; a business layer which derives value from the data service and takes decisions related to it. Interweaving of the two data chains' layers at each stage forms the 'data value chain'. 'Network management technology' includes all workstations, internet networks, application software, technical information, reference models, codes and standards required for data management for collecting and processing the biomass data. Other data-driven technologies for a robust BSC involves digital-twin technology which develops a digital clone of the physical BSC. The data obtained from the physical BSC is transmitted virtually in real-time, and the digital clone autonomously determines the necessary measures to optimize the SC without any human intervention. Thus, it is envisaged that various components of the BSC can be enhanced and paced up using AI/ML techniques.

Operational challenges

A significantly contributing element to fluctuations in the availability of biomass is its geographical and seasonal variations, as certain types of biomasses are only accessible during specific times in particular areas [26]). This poses a significant danger to the stability of the BSC. According to [31], the project's economics would suffer if biomass supply is reduced since it will require more expensive biomass (for example imported from other locations). The heterogeneity of biomass, for example, voluminous nature rendering it having low bulk density and low GCV; and its seasonal availability renders it a difficult substrate to deal with, for generation of bio-energy. Inefficient biomass handling like unavailability of catchment area guidelines for bioenergy plants, lack of technology adoption for reduction in biomass prices; logistic issues which includes lack of storage infrastructure, high cost of transportation, and wide fluctuations in the cost of biomass also affects the economics of an efficient BSC in India.

The storage facilities provide the benefit of decreasing moisture content and facilitate the evaluation of various transportation alternatives through many nodes, thereby establishing a stable and dependable supply of biomass to optimize process capacity utilization. High interest rates on financing resulting in increased storage expenses, coupled with lack of transparent trade finance alternatives to establish a structured storage facility are the issues with a proper storage mechanism in a BSC.

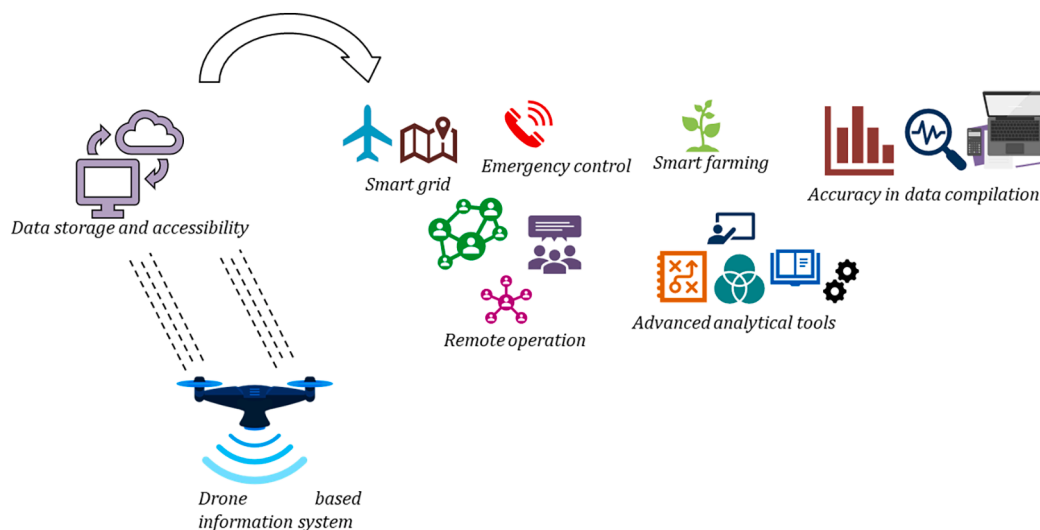


Fig. 2. IoT driven data analysis.

The logistics cost adds up due to farmers' reluctance in the proper disposal of biomass and due to the absence of an effective method for exchanging biomass for economic benefit. Dispersed and smaller agricultural lands are distant from the industrial zone and therefore numerous smaller trips for collection, aggregation, and processing contribute to increased costs.

Additionally, a few studies have found that the harvesting of different crops is impacted by climate change [32]. Climate change, namely alterations in average temperature, humidity, and rainfall, will ultimately affect the distribution and productivity of crops through changes in soil conditions [26]. As a result, this will affect the availability of biomass and make the BSC more vulnerable. Various strategies can be considered to address the aforementioned challenges. Conducting agronomy research at the beginning of the SC is crucial in order to minimize the supply risk discussed before [33]. The goal of agronomy research is to identify strategies for cultivating crops that can withstand climate change. Supply unpredictability is another significant obstacle to the growth of the bio economy. To reduce the supply burden, several strategies can be implemented in the downstream processing sectors, while also ensuring high crop and biomass yields in the upstream. Improving the total conversion efficiency is the first step towards achieving this. Increased conversion efficiency enables the production of a greater quantity of products using the same quantity of raw materials. Researchers ought to keep exploring ways to improve this kind of manufacturing efficiency.

Expansion of the biomass industry is mainly affected by inefficient resource management and reliance of the small plantation owners on a third-party supply which trades them at market price. BSC gets affected as the share of biomass being used for several other purposes like mulching, composting and animal feeding is not accounted for [34]. The fluctuation in the price of biofuel is caused by the fact that biomass is not consistently available throughout the year. Another feature of biomass, its low energy density making it difficult to acquire land for harvesting and storage. Additionally, presence of moisture in the biomass renders a high cost of logistics which makes it energetically and economically unfavorable to transport to long distances. To prevent the degradation of biomass and maintain its calorific content, it is necessary to carry out suitable pre-treatment. This involves investing in technology and results in increased production costs for biomass [35].

Financial challenges

The economy of a BSC is dependent upon cultivating, harvesting, human resource, raw materials cost, and biomass-to-bio-energy conversion process. However, the economics of a BSC can be deciphered well by developing an Economic Life Cycle Assessment model [24]. The BSC cost is evaluated in three stages: operational, tactical, and strategic cost, using a linear model [36]. The economics of a BSC is also affected by low return on investment cost, which can be resolved by multi-objective-oriented optimization model [37]. This would help in analyzing the annual and operational cost simultaneously. Furthermore, the absence of a specific strategy for the ex-situ management of agricultural residues discourages businesses from engaging in the aggregation of crop leftovers.

The Indian BSC for bio-energy generation lack a pricing mechanism in the upstream BSC, i.e., on the supply side of the feedstock. There's an opacity in the pricing mechanism, which is moreover dominated by the demand-side, causing a disproportionate participant representation, and hence an increase in the biomass price for the end-users. Although the price of the biofuel has been fixed by the government in a futuristic point of view, but the price of the biomass has been left for the market forces. This disrupts the link between the upstream and downstream sides of the BSC, thereby rendering the SC unsustainable.

Social challenges

Different levels of a BSC would require a coordinated plan of action between the stakeholders. A BSC has an active participation from

stakeholders belonging to small and medium enterprises who focus on gaining profit margins and also pose competition amongst themselves. This mutual competition amongst the stakeholders would be challenging for an effective collaboration in the industry. Nevertheless, the problems of competition can be effectively tackled through the utilization of game-theory and agent-based models. Game theory model allows the decision makers to select and work upon the unique interest of the stakeholders in the BSC and distribute the profits gained therefrom amongst them, on the basis of their contribution to the SC [38]. Agent-based models incorporate the participation of stakeholders as a group of interacting agents. Their interactions are replicated in order to measure the benefits resulting from their acts in the social context [39]. Hence, awareness of potential benefits derived from collaborations would motivate stakeholders to engage in the BSC for the purpose of exploring such collaborations. Another tool for enabling the transparency of the BSC is Blockchain technology, which is a virtual platform which connects all stakeholders in a SC by providing a real-time information on biomass availability, quality and origin, without the involvement of a third-party. It also helps the stakeholders to decipher whether their BSC is operating at an optimal level. However, the lack of awareness of the blockchain technology and its advantages also renders BSC less efficient.

Energy security problems may clearly be solved in large part by biomass supply networks. Adopting the strategy of implementing corporate social responsibility (CSR) can be a pragmatic method for businesses to contribute to the community, with the aim of enhancing investor and customer trust in the company. For example, companies may contribute to the development of a favorable business image by providing local residents with suitable and enough healthcare, social security, education, food distribution, and technological innovation.

Other challenges

Biomass being a spatio-temporal resource is seasonal in nature and scattered regionally and the sector is largely unorganized. This brings a lot of uncertainty in biomass prices both seasonally and regionally. Further biomass often requires physical, chemical, biochemical or thermochemical pre-treatments before conversion to energy significantly adding to its cost of operations. Other major issues that the BSC suffers in the economic front are the competition of biomass price with coal prices for thermal applications, competition of biomass-based power with other renewable sourced power prices per unit, cross competition for biomass between different bioenergy technology plants in a region, under developed market and limited involvement of private players. On the suppliers' side, there's an insufficient choice in biofuel types and varieties, and the absence of a framework to assess supplier performance and quality metrics. This leads to an uncalled rise in price of biomass and associated components, which increases the net cost of the overall SC.

BSC in India also lacks the presence of an e-market place where the sale and procurement of biomass is done on an online platform, without the hassle of the farmers and the stakeholders physically visiting the farms, offices, and plants for the transaction. Biomass being a scattered market in India requires an e-market place for biomass which can act as digitally enabled biomass bank, connecting the farmers to the market with significant ease of accessibility.

The effective implementation of every bio-energy project relies on the proficient administration of the BSC, as the cost of bio-energy is a crucial factor in determining its economic viability. Integration and coordination between all parties, as well as a smooth flow of information and goods are essential for any SC's success. Even though there are a lot of ongoing studies and research projects looking at the economic viability of biomass-to-value-added product processes, investors are still hesitant to put money into the biomass sector due to a perceived financial risk involved [40,41] states that the absence of investors leads to a failure in obtaining the necessary facilities, technology, and equipment. Furthermore, the fierce rivalry posed by traditional fuels significantly influences the profitability of biofuels by exerting a

substantial influence on the local gasoline prices [42]. Decentralization of bio-energy projects would mean that in order to reduce the logistic cost, the bio-energy plants are constructed in sites nearby the biomass production field. This would enable the energy storage and consumption in the areas nearby the biomass production and energy generation sites [43]. However, decentralization of bio-energy generation systems is not economic to scale up due to the fact that there still exist many centralized fossil-based energy systems which are being provided subsidies by the government. Therefore, more number and higher subsidies are required to bring the biomass-based energy systems at par with the fossil-based power plants. Also due to bio-energy decentralization and poor profitability, the participation of investors in biomass power generation industry would decline subsequently [44].

BSC case studies: Global scenarios and key takeaways

Globally, the BSCs have been modelled mainly from the perspective of both economic and environmental viability. Various mathematically modelled BSCs (Table 4 indicate that when the price becomes a constraint at different stages of a BSC, then a mathematical modelling of the SC can ease up the finance of the entire BSC, rendering it economically feasible for the farmers, suppliers of the biomass, logistic operators, stakeholders and producers of the bio-energy. Some of the key takeaways from the global SC for the Indian BSC are presented in this section.

The above studies have opened doors for the India-based BSC modelers in many different ways. One of the major takeaways was to focus on how incentives and carbon tax would encourage the bio-energy producers to shift their technology by replacing the biomass from first to second-generation. The primary reason for encouraging the shift was to adhere to the societal significance of the primary biomass to use it as a food rather than a fuel, and instead use the second-generation biomass for fuel as it was left over from the crop harvest. Therefore, the government should bring in policy changes so that the bio-energy producers shift their SC to second-generation biomass-based rather than the first-generation SC. Subsequently, higher emission tax should be levied on first-generation BSC, so that there is a forceful shift to second-generation BSC in order to induce higher profit. A pictorial depiction of the solutions to strengthen the economics of a BSC in India is shown in Fig. 3.

The BSCs prioritized the economic and environmental objectives of creating a sustainable BSC by maximizing profits and minimizing emissions. They emphasised on addressing social needs by offering financial incentives to bio-energy producers who use second-generation biomass instead of first-generation, in order to promote food security. As the transportation cost of biomass is highly dependent on the rising fuel prices, it becomes imperative to design a SC whereby the location of the bio-energy facility is nearby a site where the unused biomass is currently available. This would minimize the emissions caused from biomass transportation.

Utilizing forest wastes for forest biomass energy can help reduce CO₂ emissions and generate income for eco-entrepreneurs. A multi-objective linear programming (MLP) model can be used to assess the trade-offs between the environmental and economic advantages of all nodes in the BSC of forest biomass. This would aid in a considerable reduction in cost of transportation and chipping nodes.

For a low-cost SC, the enterprise should strengthen the role of farmers in the forest BSC so that the farmers timely harvest the biomass and aid in a stable flow of the SC. This could be done by establishing a long-term contract with the farmers and providing them subsidies for an uninterrupted supply of biomass. Enabling the farmers to use high-end equipment like chain-saws in forest biomass would also shorten the time of supply and decrease the manual work for them.

Moisture content and the distance from the biomass location to the processing facility significantly contribute to a cost-effective biomass transportation scheme, which need to be taken in account while developing a BSC. For an Indian scenario where both moisture content and

transportation cost of biomass is high, it becomes imperative to reduce the moisture content of the biomass substantially before transporting to the storage location. This would not only increase the quantity of biomass transported per trip, but also it would reduce the transportation cost of the biomass leading to development of an efficient BSC. In order to reduce both transportation costs and carbon emissions, it is necessary to create a multi-objective SC model that incorporates other models to make strategic and optimal decisions in the BSC. In India, the primary goal of the BSC is to decrease carbon emissions. Consequently, the model devised would opt for larger vehicles for the transportation of biomass. This would enhance energy security, foster the adoption of clean energy, and facilitate the sustainable growth of associated sectors.

Lastly, the involvement of middlemen and chipping plants in the route of the BSC needs to be incorporated to reduce the transportation distance and cost of the entire this SC node. The technology advancement and availability of biomass handling equipment is limited in India and it calls for the involvement of middlemen and small-scale decentralized handling plants to reduce the cost of the forest BSC.

Policies to support BSC in India

Capital and other investments in bio-energy sector can be enhanced through policy support. A proper policy implementation would be an efficient channel to support the financial mechanism of a BSC. In the past, limited policies existed in India on bio-energy and BSC. As per a report from PwC India, the sources of biomass feedstock to be used in the BSC needs to be thoroughly understood. Only 31 % of the surplus agri-biomass available in India has been utilized for bio-energy production. Thus, there should be a focus on potential sources for bio-energy production in India, such as non-food crops residue and organic waste which would have a better or equal calorific value. Cheaply available forest biomass like pinewood and saw wood can also act as potential feedstock for bio-energy production. Therefore, the establishment of sustainable and cost-effective BSC is a major need in India. In the last couple of years several policies have come up as described in Table 5.

Projections of future biomass demand and supply in India

According to recent forecasts by IEA in 2021, India is expected to contribute to around 25 % of the global increase in energy demand from 2019 to 2040. This makes India the country with the highest rate of energy consumption growth worldwide. In combination with announced country-level policies aimed at reducing fossil-fuel derived energy sources and obtaining regional net-zero emissions by 2070, an increased reliance on bio-energy and an efficient BSC is needed. In order to meet the growing demand for biomass-fired electricity and the integration of bio-energy into many sectors, there will be a need to enhance the supply of bio-energy feedstocks. The growing need for a cost-effective BSC, along with rising food consumption, might further strain the country's water resources, land utilization, and food security [45–49]. India is expected to face more pressure on its energy, water, and land resources in the future due to a combination of factors such as predicted economic growth, rising demand for bio-energy, and climate-related changes in water availability [50]. The energy, water, and land stressors mentioned can significantly affect food security and the market price of agricultural goods. Therefore, it is crucial to conduct investigations to comprehend the wide-ranging consequences of the growing demand for bio-energy. In recent times, there have been national studies conducted to analyze the interconnections between energy-water [51–53,70]; and food-water systems in India [54]. However, with increasing pressure to develop environmentally and economically efficient BSC in India, the number of studies which focus on the complex interactions, trade-offs, and synergies across energy, water, food, and land-use sectors remains limited [55,56]. A recent study, utilizing an integrated human-Earth system model, found that with the demand for electricity potentially tripling between 2020–2050,

Table 4

Biomass supply chains developed by researchers, with their objectives, key findings, limitations on economic aspects.

Biomass	Tools/methodology used	Objectives	Limitations	Key findings	Reference
Corn-stover	Mathematical modelling	<ul style="list-style-type: none"> Incentive scheme and emission tax to force/motivate the bioethanol producers to shift the SC from corn based to corn-stover based, to preserve the social value of corn as food and to encourage the use of cellulosic corn-stover in the SC 	<ul style="list-style-type: none"> The profit from first-generation SC is higher and emission is lower as compared to second-generation SC. 	<ul style="list-style-type: none"> Government to pay \$0.8495 per gallon of bioethanol produced to corn-based SC to shift the technology to corn-stover based so that the profit from both SCs is equal a higher carbon tax per kg CO₂e has to imposed on corn-based SC, and lesser on the corn-stover based, for the shift of the SC to happen 	[59]
Forest biomass: The remains of sandy shrubs, wood chips, and waste wood products.	Multi objective linear programming	<ul style="list-style-type: none"> To evaluate the trade-offs between the environmental and economic advantages of all components of the BSC, which are related to forest biomass. 	<ul style="list-style-type: none"> Limited involvement of farmers Long transportation routes and increased SC cost therefrom 	<ul style="list-style-type: none"> Optimization results suggested that a SC cost \$98.4 thousand less compared to market value of the existing SC A significant reduction in CO₂ emissions was observed in the optimized SC (60.6 x 10³ kg CO₂) as compared to the existing one 	[60]
Timber	Analytical Hierarchy Process (AHP) and Geographical Information System (GIS)	<ul style="list-style-type: none"> Mapping of the most favorable location of a biomass plant Impact of moisture content on transportation node of the BSC 	<ul style="list-style-type: none"> The biomass availability and biomass processing plant are located far apart. High moisture content 	<ul style="list-style-type: none"> Three biomass plants located within an 80 km radius were determined to be the optimal choice for Tasmania's future bio-energy plan. The reduction in moisture content from 55 % to 40 % led to decreased transportation expenses in the BSC. 	[61]
Poultry farm	GIS, AHP and multi-objective mixed integer liner programming	<ul style="list-style-type: none"> To determine the network flow, electricity generated, ideal number, placement, and dimensions of the biogas facility. The effect of maximum distance parameter and purchasing price on economics of the BSC 	<ul style="list-style-type: none"> Application of the study to different biomass types 	<ul style="list-style-type: none"> The minimum distance of the entire SC was 1006 km, with the maximum annual profit over \$7 million the maximum distance (maxi distance) between the farm and facility should be 50 km 	[36]
Generic biomass	Stochastic linear programming and fuzzy linear programming model	<ul style="list-style-type: none"> Analyze the economic cost and assessing the carbon emissions produced by various categories of trucks. The effect of uncertain factors stemming from demand in the BSC. 	<ul style="list-style-type: none"> Carbon emissions from larger carrying capacity trucks 	<ul style="list-style-type: none"> small trucks, when used for commuting, were economical, but the carbon emissions were higher 	[62]
Lignocellulosic biomass	Process Network Flow Analysis (PNFA)	<ul style="list-style-type: none"> Analyze the impact of biomass transportation on the entire SC. 	<ul style="list-style-type: none"> Identifying the best possible degradation mechanism in the SC for lignocellulosic biomass 	<ul style="list-style-type: none"> Transportation cost contributed 9–12 % of the overall cost which is low compared to other research which shows that transportation cost is often 20–40 % of the overall cost 	[63]
Agricultural biomass	Operational research, GIS, mathematical modelling, economic and sensitivity analysis	<ul style="list-style-type: none"> Optimization of agri-BSC management 	<ul style="list-style-type: none"> The low energy density, scattered distribution, and seasonal variability of agricultural biomass result in significant costs for collecting and transporting the biomass. 	<ul style="list-style-type: none"> The optimal biomass supply cost turned out to be around 181 Chinese Yuan (CYN) per ton, which was lower than the cost of the actual situation Purchase cost accounted for 31 %, transportation cost for 32 %, followed by loading/unloading (15 %), pretreatment (12 %) and Centralized storage sites (CSS) (9 %) The operational costs, the labor cost accounted for 36 % of the total cost, followed by purchase (31 %) and equipment (24 %) cost 	[64]
Wood	Forest Reduction Cost Simulator (FRCS)	<ul style="list-style-type: none"> Develop an economic SC model to calculate the cost of woody biomass by considering the stumpage price, harvesting and chipping expenses, and transportation costs associated with delivering the biomass to the biorefinery. 	<ul style="list-style-type: none"> The cost of chipping only biomass was more responsive to changes in input parameters compared to the cost of proportioned biomass. 	<ul style="list-style-type: none"> Cost of the delivered biomass was estimated at \$30/ green ton (GT), of which 70 % and 7 % was incurred by the harvesting cost and contractor's profit, respectively 	[65]

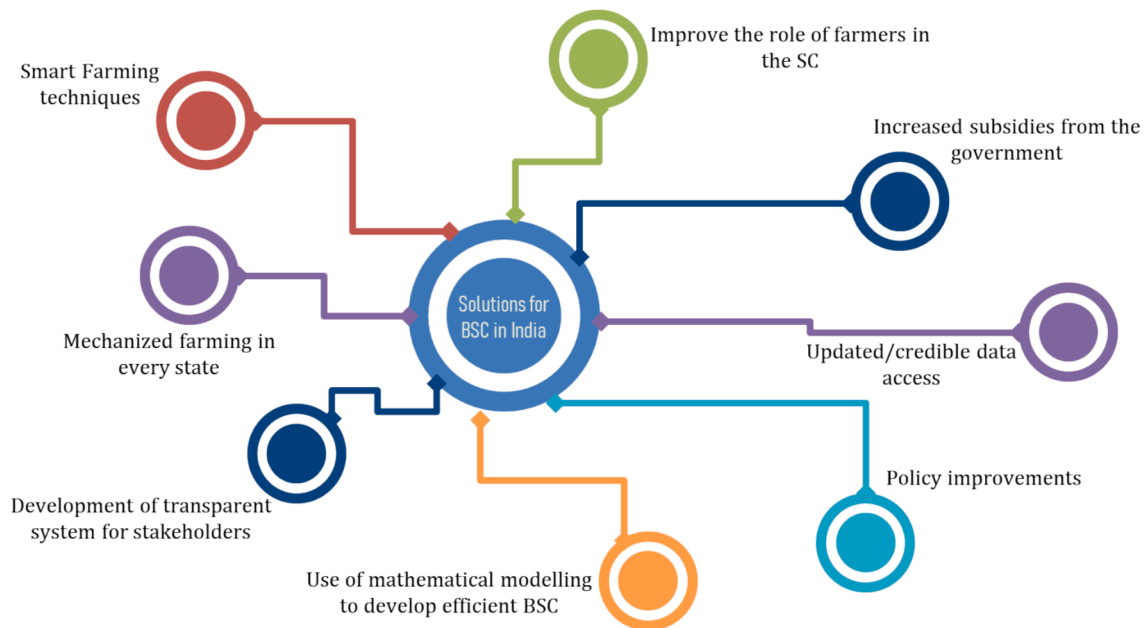


Fig. 3. Pictorial depiction of solutions to strengthen the economics of a BSC in India.

the amount of generation from biomass derived sources may increase by over an order of magnitude in the same timeframe, reaching nearly 200 Terawatt hours (TWh) by 2050 in a carbon mitigation scenario [55], which would have a direct effect on the biomass demand and its SC. However, this depends on the mix of cropping residues, purpose-grown grasses, and other wastes highlighted throughout this review, each with their own energy potentials [55].

Key learnings and contributions from the review

The key contributions of the review are presented below

- i. The economic viability of BSC for bioenergy production gets influenced by several interrelated processes, with the key factors being data availability and analysis, market development, digitization, technology and human capital, transportation and logistics, policies, governance, and institutional mechanisms recognized as the primary components.
- ii. BSCs in India face some major challenges: Data collection issues (unavailability of credible data, limited access to updated data, incompetent data chain), Data acquisition (lack in the extensive usage of Advanced Data Analytics and Forecasting techniques), Operational challenges (biomass availability, voluminous nature of biomass, supply unpredictability, and logistic issues), Social obstacles (coordination of action between the stakeholders, mutual competition).
- iii. Assessing economic and environmental sustainability of a BSC necessitates the availability of updated data from a single source, presence of skilled manpower to analyse the data, evaluation of GHG emissions and transportation/handling costs linked to biomass. Scientific development of more efficient and field-validated economic BSC operational models and conducting comprehensive techno-economic analysis is essential to stimulate interest among industry stakeholders and promote increased investment in biomass-based enterprises.
- iv. The major takeaways from the mathematically modelled case studies on the economics of the BSCs developed globally include: the provision of incentives and a carbon tax to transition the BSC from first to second-generation biomass, the optimization of bioenergy plant locations, the reduction of CO₂ emissions, the

generation of income for eco-entrepreneurs, the enhancement of farmers' roles, the development of a multi-objective SC model that integrates additional models for strategic and optimal decision-making in the BSC, and the engagement of intermediaries and chipping facilities along the BSC (Table 4).

- v. Various governmental organizations and ministries across India have set forth various degrees of financial allocations towards the development and implementation of BSC for which awareness needs to be created amongst the stakeholders (Table 5).
- vi. Biomass demand in India is projected to increase as population and GDP increase in the coming decades. Without an adequate understanding of the BSCs that are currently established across the country, and those being considered in the present, policy-makers cannot gain insight to where shortcomings may arise in the future.

Recommendations

Some of the recommendations derived from the review process for achieving economic sustainability for the development of efficient BSCs in India are as follows:

(a) Innovative digital solutions and business models for BSCM: Digital solutions for efficient BSCM that will enhance transparency are essential for fostering a healthy relationship between suppliers and customers. Technology can facilitate the interconnection of several local market clusters to optimize the SC. They provide access to historical graphical biomass price trend data from previous services, which would immediately assist suppliers and buyers in understanding current biomass price patterns. ML algorithms can evaluate past data to enhance demand forecasts. This will ensure a sufficient biomass supply to satisfy demand, while avoiding surplus inventory. AI-driven optimization techniques can identify the most efficient routes for biomass transportation. These techniques can consider variables such as traffic conditions, distance, and fuel expenses. AI can also be used to trace the origin of biomass and guarantee its sustainable sourcing. This can assist in fulfilling the increasing need for RE sources. A chatbot in many regional languages that offers accessible solutions to farmers is necessary to provide nationwide service across India. Effective SC management can incorporate contemporary technologies like as Internet of Things (IoT), AI, and blockchain to enhance tracking, inventory control,

Table 5
Bio-energy policies developed in India.

Stakeholder involved	Bio-energy scheme	Objectives	Financial Implications/ Support Available
Ministry of New and Renewable Energy (MNRE)	Waste to Energy Programme	<ul style="list-style-type: none"> To facilitate the establishment of Waste to Energy initiatives aimed at producing Biogas, Bio-CNG, Power, or producer/syngas from urban, industrial, and agricultural wastes/residues. Central Financial Assistance (CFA) is given to project developers and service charges are supplied to implementing/ inspection agencies upon the successful completion of Waste to Energy plants. 	<ul style="list-style-type: none"> Financial assistance for setting up Waste to Energy plant: <ol style="list-style-type: none"> ₹ 4 Cr (462,232 USD) per 4800 kg/day (for Bio-CNG generation from new biogas plant) ₹ 3 Cr (346,674 USD) per 4800 kg/day (for Bio-CNG generation from existing Biogas plant) Maximum CFA of ₹10 Cr (1.155 million USD) project for both cases
	Biomass Programme	<ul style="list-style-type: none"> It aims to provide assistance for the establishment of Biomass Briquette/ Pellet manufacturing plants and the implementation of Biomass (except bagasse) based co-generation projects in businesses across the country. 	<ul style="list-style-type: none"> Financial assistance available under the programme is as follows: <ol style="list-style-type: none"> Briquette Manufacturing plants: ₹ 9 Lakhs (10,400 USD) per metric ton/hour (MTPH) Non-torrefied pellet manufacturing plant: ₹ 21 Lakhs (24,267 USD) per MTPH or 30 % of the capital cost considered for the plant (whichever is lower, upto maximum ₹ 105 Lakhs (121,336 USD) per project) Torrefied pellet manufacturing plant: ₹ 42 Lakhs (48,534 USD) per MTPH or 30 % of the capital cost considered for the plant (whichever is lower, upto maximum ₹ 210 Lakhs (242,672 USD) per project)
	Biogas programme	<ul style="list-style-type: none"> Establishing a biogas plant to provide clean fuel for cooking, lighting, thermal energy, and small-scale power generation. This would lead to a reduction 	<ul style="list-style-type: none"> A budget allocation of ₹ 100 Cr (11.55 million USD) for the fiscal years 2021–22 to 2025–26.

Table 5 (continued)

Stakeholder involved	Bio-energy scheme	Objectives	Financial Implications/ Support Available
		<ul style="list-style-type: none"> in greenhouse gas emissions, improved sanitation, empowerment of women, and increased employment opportunities in rural areas. Beneficiary should have their own land/space of about 50–60 m² Availability of cow/feedstock and regular water supply Small biogas plant projects required 1 m³ to 25 m³ Medium biogas plant projects required 25 m³ to 2500 m³ 	
Ministry of Jal Shakti	GOBAR-dhan Galvanizing Organic Bio-Agro Resources Dhan	<ul style="list-style-type: none"> To assist rural communities in effectively managing their livestock waste, agricultural waste, and all other forms of organic waste. The process of converting organic waste, particularly animal manure, into biogas and fertilizer for utilization in rural areas. Promotes rural entrepreneurship, employment and income-generation opportunities. Assists in controlling the spread of diseases transmitted by vectors by implementing efficient waste disposal methods in rural areas. 	<ul style="list-style-type: none"> The operational rules for Phase-II of Swachh Bharat Mission-Gramin SBM(G) stipulate that financial aid of up to ₹ 50 Lakhs (57,779 USD) per district to be granted from 2020–21 to 2024–25 to establish cluster/community level biogas facilities.
Ministry of Power (MoP)	National Biomass co-firing Policy SAMARTH-Sustainable Agrarian Mission on use of Agri-Residue in Thermal Power Plants	<ul style="list-style-type: none"> The objective is to convert biomass into power using environmentally friendly and cost-effective methods, while implementing appropriate market mechanisms to mitigate the worsening of air quality. Mandates a 5 % biomass co-firing in Thermal Power Plant To engage in research and development activities focused on designing 	<ul style="list-style-type: none"> The price mechanism for the purchase of pellets by Thermal Power Plants has been fixed by the government.

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Table 5 (continued)

Stakeholder involved	Bio-energy scheme	Objectives	Financial Implications/ Support Available
Ministry of Petroleum and Natural Gas (MoPNG)	National Biofuels Policy	<p>boilers capable of effectively managing increased levels of silica and alkalis found in biomass pellets</p> <ul style="list-style-type: none"> To facilitate the resolution of limitations in the SC of biomass pellets and agro-residue, as well as their transportation to power plants. To address regulatory concerns related to biomass co-firing. Biofuels are classified into different categories to facilitate the provision of suitable financial and fiscal incentives for each category. The categories include “Basic Biofuels” such as First Generation (1G) bioethanol and biodiesel, as well as “Advanced Biofuels” like Second Generation (2G) ethanol, Municipal Solid Waste (MSW) converted into drop-in fuels, Third Generation (3G) biofuels, and bio-CNG. Encourages the establishment of SC mechanisms for the production of biodiesel using non-edible oilseeds, used cooking oil, and crops with short gestation periods. The National Biofuel Coordination Committee has approved the utilization of excess food grains to produce ethanol for blending with petrol. The recent revisions made by the Cabinet have accelerated the goal of achieving 20 % ethanol blending in petrol, moving the 	<ul style="list-style-type: none"> India frequently revises the set pricing of ethanol, taking into account the type of feedstock used. This practice aims to facilitate sales and lower the Goods & Service Tax rate from 18 % to 5 %. India also offers an interest subvention option for newly constructed or upgraded facilities.

Table 5 (continued)

Stakeholder involved	Bio-energy scheme	Objectives	Financial Implications/ Support Available
	SATAT-Sustainable Alternative Towards Affordable Transportation	<p>deadline from 2030 to 2025–2026.</p> <ul style="list-style-type: none"> To establish 5000 Compressed Biogas (CBG) facilities by 2023–24, with a production goal of 15 MMT. This will create new job possibilities and increase farmers’ income, thereby boosting the rural economy Contribute to the goal of tripling farmers’ income, creating employment opportunities for young people, and promoting renewable energy for sustainable development Encourages entrepreneurs to establish CBG factories, manufacture, and provide CBG to oil marketing organizations (OMCs) for the purpose of selling it as automobile and industrial fuels. 	<ul style="list-style-type: none"> The price mechanism for CBG offtake through Oil Manufacturing Companies has been fixed by the government. CBG prices have been indexed to the retail selling price of CNG in the market.
	CBG Blending Obligation (CBO)	<ul style="list-style-type: none"> To promote investment and streamline the establishment of 750 CBG projects by 2028–29. The presence of CBG in the country facilitates the promotion of a gas-based and circular economy, reduces the need for foreign exchange, and helps achieve the goal of net zero emissions. 	<ul style="list-style-type: none"> Promote the growth of demand for CBG in transportation and domestic sectors, replace the need for Liquefied Natural Gas (LNG) imports, and support the adoption of a circular economy. The CBO will remain optional until the fiscal year 2024–2025, after which it would become obligatory starting from the fiscal year 2025–2026. The percentages of Compressed Natural Gas (CNG)/Piped Natural Gas (PNG) consumption for the financial years 2025–26, 26–27, and 27–28 are 1 %, 3 %, and 4 % accordingly.

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Table 5 (continued)

Stakeholder involved	Bio-energy scheme	Objectives	Financial Implications/ Support Available
			<ul style="list-style-type: none"> Starting in 2028–29, the CBO will be set at 5 %. The investment amount would be approximately ₹ 37,500 Cr (4333 million USD), which will enable the creation of 750 CBG projects by the year 2028–29. The allocation is ₹564.75 Cr (65 million USD), with a subsidy limit of 50 % of the procurement cost.
	Biomass procurement machinery aid	<ul style="list-style-type: none"> To streamline the process of collecting and promoting biomass, thereby preventing the incineration of excess biomass and providing additional revenue for farmers. Furthermore, the objective is to derive economic benefits from underutilized biomass resources and agricultural waste, such as paddy straw, by converting them into CBG and organic fertilizer. The objective is to provide financial aid to CBG producers for the acquisition of biomass aggregation machinery (BAM) in order to facilitate the gathering of biomass for the first 100 biomass-based CBG plants. 	
	Ethanol Blending petrol (EBP) Programme	<ul style="list-style-type: none"> The objective is to achieve several results, including addressing environmental concerns, reducing reliance on imports, and promoting the farm industry. The OMCs determine the annual quantity of ethanol to be procured, as well as the procurement price, which is based on damaged and surplus food grains (if applicable). The government, on the other hand, sets the procurement price for ethanol derived 	<ul style="list-style-type: none"> The government is providing interest subvention at a rate of 6 % per annum or 50 % of the interest charged by financial institutions, whichever is lower, for five years, including a one-year moratorium. This initiative has led to investment opportunities exceeding ₹ 40,000 Cr (4622 million USD), benefitting both urban and rural areas.

Table 5 (continued)

Stakeholder involved	Bio-energy scheme	Objectives	Financial Implications/ Support Available
		from sugarcane based raw materials, considering the current situation in the sugar sector.	
	Scheme for the development of pipeline infrastructure (DPI) for the injection of CBG	<ul style="list-style-type: none"> For the development of pipeline infrastructure for the injection of CBG compressed biogas in the city gas distribution network 	<ul style="list-style-type: none"> Financial outlay of ₹ 994.50 Cr (115 million USD) Shall provide financial assistance for creating CBG-CGD (City Gas Distribution) grid connectivity for 100 CBG projects and create ecosystem for offtake of CBG with reduced logistic cost.
Ministry of Chemicals & Fertilizers	Market development assistance (MDA) for organic fertilizers	<ul style="list-style-type: none"> MDA will be provided at a rate of ₹ 1500/MT (17 USD/MT) for the sale of Fermented Organic Manure (FOM), Liquid Fermented Organic Manure (LFOM), and Phosphate Rich Organic Manure (PROM). 	
Ministry of Agriculture & Farmers Welfare	Agriculture Infrastructure Fund	<ul style="list-style-type: none"> To facilitate the acquisition of a debt financing facility over a period of time for investment in feasible projects related to post-harvest management, infrastructure, and community farming assets. This initiative aims to enhance agricultural infrastructure in the country by providing incentives and financial assistance. Scheme targets to provide following benefits: The post-harvest management projects encompass several aspects such as SC services, which include e-marketing platforms, warehouses, silos, pack-houses, assaying units, sorting and grading units, cold chain facilities, logistics facilities, 	

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Table 5 (continued)

Stakeholder involved	Bio-energy scheme	Objectives	Financial Implications/ Support Available
		and primary processing centres.	
		1. Enhanced marketing infrastructure to enable farmers to directly sell their products to a broader consumer base, hence increasing the value they receive for their produce. This will enhance the overall revenue of farmers.	
		2. By making investments in logistical infrastructure, farmers can minimize post-harvest losses and decrease the number of middlemen involved in selling their products in the market. This will enhance farmers' autonomy and enhance their market accessibility.	
		• By using Credit Guarantee, incentive, and interest subvention, lending institutions can mitigate their risk and provide loans with reduced levels of uncertainty. This strategy will facilitate the expansion of their consumer base and the diversification of their portfolio.	

and transparency. IoT and smart sensors provide real-time monitoring of biomass quality, moisture levels, and storage conditions, thereby providing optimal feedstock for conversion operations. Blockchain technology can be utilized to monitor biomass from its source to the final product, guaranteeing transparency, traceability, and sustainability within the SC. Business models like development of e-market place of biomass which facilitates direct purchase of biomass from farmers, opportunity for farmers to rent equipment, scheduling & tracking of supplies via local transportation, and managing storage facilities via local employment creation are the benefits a BSC can obtain through an e-market place.

(b) Effective solutions to storage and logistic issues in BSCM: It has been vividly discussed that biomass storage has been a persistent issue in a BSC, as it is the limiting factor which decides the perishability of the biomass in the entire SC. Therefore, the storage area must be waterproof, fully insured, and arranged with designated fire lanes.

Design of silage techniques for biomass preservation by regulating moisture content and minimizing microbial activity during storage, contemporary air-drying systems which offers advanced moisture reduction in biomass prior to storage, thereby mitigating the danger of degradation and spontaneous combustion are much needed to solve the storage issues of the BSC. These techniques would not only help combat the crop residue burning but also provide a suitable storage area for surplus biomass deposits, rendering the development of an economically stable BSC. For solving the logistic issues of a BSC, mathematically designed models need to be developed which optimizes the best possible route (in terms of distance, GHG emissions, and cost-effective) for the transport of biomass from the production and storage site to the bio-energy generation plants. Provision of subsidies from the local and state government for purchase/rent of trucks/tractors, and fuel utilization can also reduce the overall cost of the SC.

(c) Government intervention for smooth execution of the action plans, technologies and policies: The authors believe that a strategic implementation of the governance mechanism needs to be implemented at national, state, district and block levels. Monitoring and verification of the BSC at grass root level with special emphasis on the participation of farmers community at large. Satellite imagery from state remote sensing technology needs to be leveraged, mobile-based applications and smart devices need to be invented and used for logistics optimization of the SC. This would not only help in reducing the carbon footprints, but also prove to provide an economic BSC. A roadmap for technology adoption which would involve mechanized harvesting, smart farming and big-data analysis techniques should be adopted to develop a techno-economic BSC. An action plan with a bottom-up approach involving the stakeholders like village governance (*panchayat*), Block Development Officers (BDOs) and state regulatory authorities should be implemented so that the optimization of a BSC be supplemented with added incentives/subsidies which would render the SC economical and environmentally sustainable.

(d) Financial provisions and support: Enhancement of credit facilities to support the procurement of biomass, consolidation of agricultural equipment, and provision of operational capital for FPOs, VLEs, and individual farmers via banks at reduced interest rates would stabilize the economy of the farmers' budget in the BSC. Specialized insurance products offered by insurance companies for biomass and biofuels storage, incentives for farmers in the form of subsidies or manure to encourage the provision of biomass, to be granted within a designated timeframe encourages the farmers to invest productively in a BSC. Implementation of a circular economy approach in production of bio-energy which also generates additional by-product (glycerol, a by-product from biodiesel generation; FOM, a by-product from biogas production; distillers' grain, a by-product from bioethanol production). Support schemes should be launched for research, value addition and development of market for the by-products. These by-products can be put to alternative use (glycerol as a solvent, FOM as a soil amendment, distillers' grain as an animal feed) which would ensure long-term sustainability. Enhanced knowledge dissemination among stakeholders the laws enacted by governmental entities in the domains of bioenergy and environmental sustainability is additionally call-for-action by the central and state government in India in order to ensure an efficient BSC development, both environmentally and economically.

Conclusion

The economic aspects of any BSC need to be of primary importance before setting up a biorefinery. Although it is imperative to account for the environmental sustainability of any BSC, the economic considerations need to be researched upon extensively before designing a SC. Various case studies around the world discussed in this review helps to determine the cost considerations that is incurred in different BSCs and also awakens us to implement the same in other feedstock SCs as well. The models that have been designed by the researchers should be

applied by various SC experts wherever the need arises. This would give the contractors and stakeholders a clearer picture of what could be the approximate cost incurred starting from the harvest of the biomass to the production of the biofuel. Subsequently, the bottlenecks faced during the study of the economics of BSC in general and those in India has been discussed and the probable solutions explained. Lastly, the various policies with respect to economics of a BSC existing in India has been discussed.

To combat the economic instability in the BSCs in India, the identification of problems like data acquisition, incredibility of data, unavailability of updated data, high moisture content and heterogeneity of biomass affecting the storage and logistics of the SC, high transportation cost, lack of skilled manpower and modelers, absence of stakeholders involvement, lack of subsidies and insurances, and adherence to unscientific optimization techniques; and thereafter developing means to overcome these challenges is required. The global case studies on the BSC guide the Indian BSC to focus on how incentives and carbon taxation could motivate bio-energy producers to transition their technology from first to second-generation biomass, position bio-energy facilities near sources of unused biomass, employ forest waste for biomass energy to mitigate CO₂ emissions and generate revenue for eco-entrepreneurs, and enhance the involvement of farmers in the forest BSC. These solutions are wholly dependent on scientific modelling of the SC, and proper planning of each component of the biomass-to-bioenergy SC. The active involvement of the central and state government, stakeholder, entrepreneurs, and data scientists in designing the BSC is the only way to render a SC economically sustainable.

Thus, the economic aspects being critical in the development of a BSC depends on a whole consortium of activities at every node, mathematical modelling and optimization of the same and enhancement of country and state-level policies which may drastically increase the efficiency of bio-energy plants in India.

CRedit authorship contribution statement

Banafsha Ahmed: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Avinash Bharti:** Writing – original draft, Methodology, Investigation, Data curation. **Gurkamal Nain Singh:** Writing – original draft, Methodology, Investigation. **Neal T. Graham:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Ashish Bohre:** Writing – review & editing, Resources, Project administration, Formal analysis. **Meredydd Evans:** Writing – review & editing, Validation, Methodology. **Vandit Vijay:** Writing – original draft, Writing – review & editing, Conceptualization, Visualization, Validation, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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