The Dynamics Behind Sustainable Biofuels: Lessons from Latin American Supply-Chain Models

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Abstract

This paper reviews how System Dynamics (SD) has been applied to biofuel supply chain modeling in Latin America (LA) and compares these applications with studies from the rest of the world (ROW). The review examines how SD models represent supply chain structure, sustainability dimensions, economic dynamics, and policy interventions. Across both contexts, models share a similar core structure linking feedstock supply, processing capacity, production, and investment. However, their emphasis differs. In LA, SD studies more often focus on structural viability, asking whether biofuel systems can expand under constraints related to land availability, feedstock supply, food security, policy credibility, and state participation in the market. In contrast, ROW studies more commonly assume more mature market conditions and focus on transition optimization, including cost competitiveness, technology learning, and emissions reduction. The review also identifies recurring gaps. Land use and greenhouse gas emissions are commonly represented, but water remains weakly integrated as an endogenous constraint, despite its relevance for agricultural biofuel systems. Social dimensions are also underdeveloped, as most studies treat employment, rural development, and food security as aggregate outcomes rather than modeling farmers and producer groups as endogenous decision-makers. Policy assessment in both contexts relies mainly on scenario testing of mandates, subsidies, and incentives, although LA studies place greater emphasis on land and social-environmental trade-offs. The paper concludes that future SD biofuel models should better integrate farmer decision-making, water constraints, and cross-sector policy feedbacks to strengthen sustainability assessment and improve representation of biofuel transitions.

Keywords: System Dynamics; Biofuel supply chains; Sustainability assessment; Latin America; Policy analysis

1. Introduction

Latin America (LA) has long been recognized as a region with significant potential for developing a biofuel-based energy sector. Favorable agroecological conditions, large areas of arable land, and well-established industries such as sugarcane, soybean, and oil palm production provide a strong resource base for biofuel feedstock. Countries like Brazil, Argentina, and Colombia have demonstrated the technical feasibility of large-scale biofuel production, particularly for ethanol and biodiesel, supported by the existing agricultural supply chains (SC) and blending mandates [1], [2].

Despite this potential, the growth of biofuel industries across LA has been uneven and slower than expected. While Brazil has developed one of the most mature ethanol industries in the world, some countries have experienced difficulties sustaining expansion due to policy volatility, infrastructure constraints, investment uncertainty, and land use priorities [3], [4]. In many LA countries, biofuel markets have historically been shaped by government intervention through blending mandates, regulated price structures, and state programs designed to guarantee demand for domestic production. These policies are often used to create stable markets for biofuels and to support agricultural sectors that supply feedstocks [4], [5].

Understanding how institutional and structural differences influence the behavior of the biofuel SC is key to designing effective policies and sustainable goals. System Dynamics (SD) has been used to analyze biofuel systems because it can capture environmental outcomes based on feedbacks within and between feedstock supplies and policy applications. However, applications show differences between the country contexts and their system boundaries. This raises research questions, such as: Why do biofuel SC dynamics in LA differ from those observed in other regions? Are these differences primarily driven by stronger state participation in biofuel markets, by institutional and cultural characteristics of agricultural sectors, or by other structural factors influencing SC behavior? To address these questions, this paper reviews the SD literature on biofuels in and outside LA, comparing the findings with key lessons and conclusions from the modelling approaches.

2. Literature review

The following section summarizes the main findings of a literature review on SD modelling of biofuel SC, sustainability, and policy assessment. It contrasts findings from LA with those from the Rest of the World (ROW).

2.1. SC modelling

Across the reviewed literature on biofuel SCs, the SD modeling approach focuses on interconnecting capacity with feedstock. The studies capture the upstream and midstream stages of the SC, including cropping, harvesting or waste collection, feedstock processing, and fuel output. Only a subset extends to downstream components such as distribution systems, market trends, or blending mandate targets [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]. A schematic representation of the SC considered in the studies reviewed is shown in Figure 1 and Figure **2**.

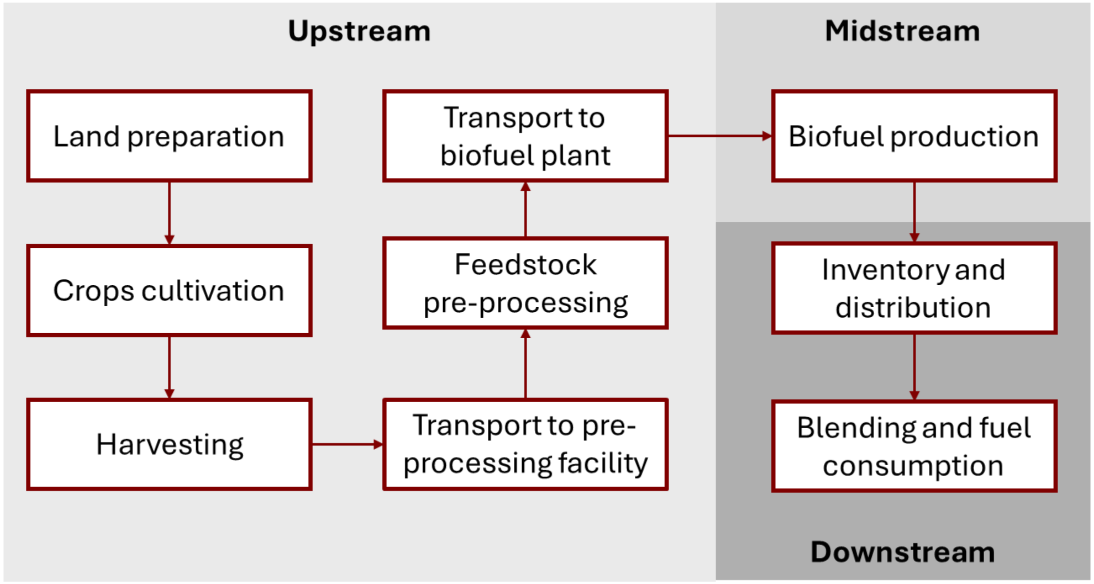

Figure 1. General SC configuration for bioethanol and biodiesel production

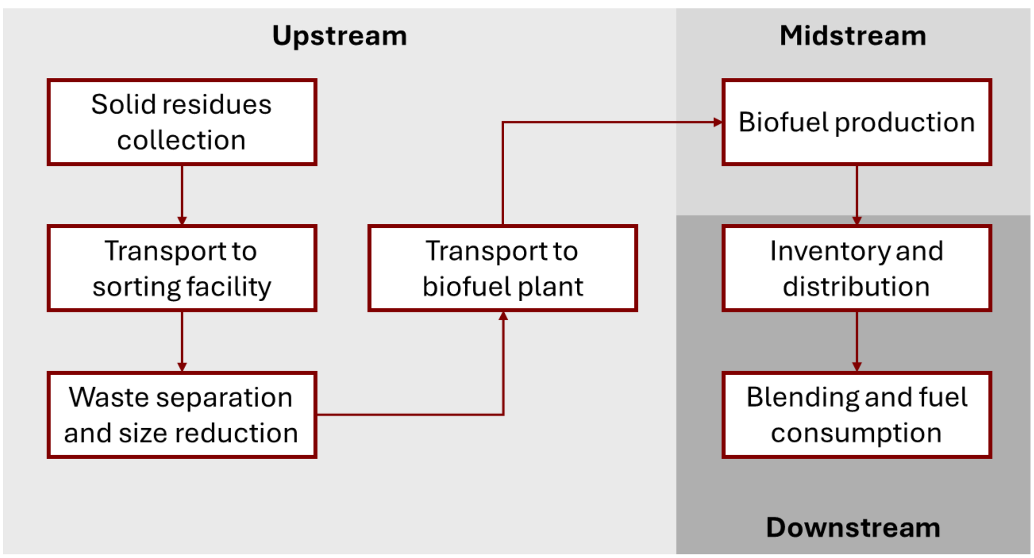

Figure 2. General SC configuration for biofuels production from solid residues

Core stocks typically include agricultural land allocated to biofuel crops or biomass availability in terms of waste mass, installed processing capacity, fuel inventories, and capital investment. Flows represent crop growth, biomass harvesting, waste collection, processing rates, and fuel consumption. Time delays are explicitly incorporated to reflect biological growth cycles and refinery construction periods. Economic components, including prices, profitability, and production costs, are frequently integrated to determine capacity expansion or contraction dynamics.

In several studies, [7], [8], [12], [14], [15], [16], [17], [18], [19], [20], land availability is modeled as a limiting stock constraining feedstock expansion, while refinery capacity functions as a bottleneck regulating fuel supply. Demand is commonly represented either as an exogenous growth trajectory or as a function of policy-induced blending requirements. When environmental variables are incorporated, they are typically assessed indirectly through fossil fuel displacement effects rather than through detailed life cycle assessment (LCA) frameworks.

2.2. Sustainability approach in modelling

Table 1 presents the main parameters used in SD sustainability modelling. These are grouped into three main categories: Social, Environmental, and Financial aspects, identified in the literature from LA and ROW.

2.2.1. Social modeling in sustainability

Across the LA studies reviewed, social aspects in biofuel SC models are mostly incorporated as an outcome of developing the biofuel market. Macro-level indicators are used to track these social benefits, like rural employment represented as a function of crop expansion or processing capacity growth, where the increased demand for biomass for biofuel production generated labor demand [9], [19], [21], [23], [28]. Food security is commonly used as a social indicator, modeled through land allocation trade-offs between biofuel crops and food crops [19], [22], [23]. Some models link biofuel production to GDP growth and, in turn, to livelihood improvements or poverty reduction through aggregated economic feedback loops [21], [26]. Poverty displacement was represented in some articles through income changes linked with agricultural employment or land reallocation, but generally, the trend was to represent the impact at a sectoral level, rather than through household or land tenure level dynamics [19], [23], [28].

In the worldwide literature, the same approach is followed in modeling the social aspects, which are treated as outcomes of the systems' expansion. Employment generation is commonly modeled as a function of production scale or investment [18], [20], [30], in contrast to LA where it is focused on rural development and economic growth. Energy security serves as a macro-level indicator of social benefits associated with reduced fossil fuel imports [7]. Food security and land rights are represented through land-use competition dynamics, similar to LA models, but sometimes also include explicit land-tenure considerations [14], [29], [31]. Some studies linked biofuel production expansion to rural development or quality of life improvements through economic growth feedback rather than direct social behavior modeling [18], [20].

Table 1 Sustainability criteria used in SD modelling in LA and ROW

Reference	Country	**Social**					**Environmental**			**Financial**				
		Rural development	Food Security	Economic growth	Energy security	Employment generation	Land use	GHG emissions	Water impact	Production cost	Profitability	Investment	Incentives	Carbon credit
Latin America														
[21]	Brazil	■		■				■	■	■				
[22]	Brazil		■				■		■				■	
[23]	Colombia	■	■					■	■	■	■			
[24]	Colombia						■					■		
[25]	Colombia	■		■			■		■					
[19]	Colombia	■	■	■			■			■				
[26]	Colombia			■			■							
[13]	Mexico						■	■						
[27]	Mexico						■		■					
[28]	South America	■		■	■		■	■	■					
Rest of the World														
[14]	Australia		■				■			■				
[8]	Europe						■	■						
[20]	Global			■		■								
[18]	India	■	■			■		■		■	■			■
[29]	Indonesia		■				■	■			■			
[7]	Latvia				■		■				■			
[30]	South Africa					■	■	■			■			
[31]	Taiwan		■				■			■	■			
[17]	USA						■	■			■			
[12]	USA		■				■							
[15]	USA						■				■		■	
[6]	USA									■	■			

2.2.2. SD evidence on land, resources, and sustainability in biofuel transitions

This review identified SD studies that examine how biofuel pathways interact with land allocation and land-use change (LUC), greenhouse gas (GHG) emissions, and water demand and impact. For each case, we report the country or region analyzed, the sustainability indicators covered, and how SD modeling was used to represent these dynamics.

- **Land allocation and LUC**

Several SD studies incorporate land availability and land-use (LU) constraints when assessing biofuel expansion; however, the way these dynamics are represented differs considerably between the LA and ROW. In LA, SD models commonly treat land allocation and land-use (LU) as central dynamic drivers of biofuel sustainability. Many models explicitly represent land as a core state variable interacting with food production, biofuel expansion, and environmental outcomes. In Colombia, early work incorporated land indirectly through production expansion dynamics [9], while later studies explicitly linked oil palm expansion to agriculture land displacement and land concentration risks affecting food security [23]. More detailed allocation frameworks distribute land among food crops, livestock, biofuel crops, degraded land, and potential arable land, demonstrating that reallocation livestock land can partially mitigate food-fuel competition [19]. Subsequent models incorporate explicit LUC dynamics, showing that prioritizing degrade land for oil palm expansion substantially reduce forest conversion and indirect land-use Change (ILUC) [26], while more recent simulations represent sugarcane area as a dynamic stock driven by productivity and demand, highlighting persistent food-fuel trade-offs [25]. Similar dynamics appear in other LA countries: in Mexico, land availability for sugarcane and sorghum directly constrains ethanol production [13], [27], while in Brazil sugarcane expansion competes with staple crops unless productivity gains offset these pressures [22]. Alternative pathways such as biodiesel derived from waste cooking oil illustrate how second-generation resources can decouple biofuel production from agricultural LU and reduce food-security concerns [21]. At the regional scale, studies emphasize that although South America has relatively abundant agricultural land, unmanaged expansion of crops such as sugarcane, soy, and oil palm can displace food production and forests, highlighting the need for LU planning, degraded-land utilization, and effective governance strategies [28], [32].

In contrast, SD applications in the ROW more commonly treat land as a structural constraint on feedstock availability or production capacity rather than as a central driver of sustainability dynamics. For example, the Biomass Scenario Model (BSM) in the United States models competition for agricultural land among crops and bioenergy feedstocks, linking biofuel deployment to crop prices, grower incentives, and land allocation decisions

[12], [15], while earlier SD models similarly considered arable land as a limiting production factor [6]. Other studies incorporate land availability within sector-specific contexts, such as forest harvesting dynamics in Canada [20], rapeseed cultivation limits in Europe [7], and feedstock land requirements in regions such as South Africa, Australia, Indonesia, and India [14], [18], [29], [30]. Overall, while ROW models typically represent land as a limiting production resource, LA models more frequently treat land allocation, LUC, and land governance as core feedback mechanisms shaping biofuel sustainability outcomes, highlighting stronger interactions between biofuel expansion, food systems, and territorial dynamics in the region.

- **Water impact**

Water use remains a relatively underrepresented dimension in SD models of biofuel systems; however, LA studies tend to integrate water impacts more explicitly than those developed in the ROW. In several LA models, water is incorporated as an environmental indicator or as part of dedicated submodules that capture resource constraints within agricultural and processing systems. For example, Colombian studies have incorporated water scarcity indices within biodiesel SC models, showing how water deficits in oil palm cultivation can reduce crop yields and generate reinforcing feedbacks between water availability and production performance [23]. More recent work models water withdrawals as a sustainability indicator based on cultivated area, irrigation practices, and crop productivity, demonstrating that without efficiency improvements, water demand may exceed sustainability thresholds [25]. Additional research highlights water-related challenges associated with ethanol production, particularly the increasing volumes of vinasse generated as a liquid byproduct requiring careful environmental management. Together, these approaches illustrate how LA studies increasingly recognize water demand as an important sustainability dimension connected to agricultural expansion and biofuel processing.

In contrast, SD studies in the ROW rarely incorporate water as a dynamic variable within system feedback structures. Even when water is acknowledged as important, it is typically treated as a contextual factor or as part of operational costs rather than as a resource subject to depletion or scarcity. For instance, in South Africa (Western Cape), water requirements for agricultural cultivation, process water, and cooling are recognized as relevant sustainability indicators; however, within the SD implementation water is represented primarily as a cost component within operational expenditures rather than as a biophysical stock or constraint [30]. Similarly, studies in India refer indirectly to water through agricultural productivity but do not explicitly simulate irrigation demand or hydrological limitations [18]. In other cases, water impacts fall outside the system boundary altogether, as observed in SD modeling of biodiesel systems in Latvia [7].

Overall, the comparison highlights a clear modeling gap in the broader SD literature. While LA studies increasingly attempt to incorporate water demand and scarcity considerations into sustainability assessments, most ROW models still omit water from the core system structure. As noted in the literature, water-related impacts are often addressed only indirectly through LCA indicators rather than through endogenous feedback mechanisms within SD models [20]. Integrating water availability, irrigation dynamics, and scarcity responses as explicit system variables would substantially improve the capacity of SD frameworks to evaluate the long-term sustainability of biofuel transitions, particularly in regions facing increasing hydrological stress.

- **GHG in SD modeling**

GHG emissions are incorporated into SD models of biofuel systems through multiple approaches, but the level of integration varies considerably between LA and the ROW. In LA, SD studies commonly link emissions to LU dynamics, feedstock choices, and broader sustainability transitions. Early work in Mexico evaluates emission outcomes indirectly by comparing fossil and biofuel contributions under different structural scenarios, showing that ethanol provides only limited mitigation benefits if systemic constraints such as low productivity persist [13]. Later studies in Colombia incorporate more explicit environmental indicators. For example, S. Bautista et al. [23] integrate GHG emissions and air-quality pollutants into biodiesel SD, revealing feedbacks between crop productivity, land expansion, and emissions. Bernarte et al. [26], extend this approach by explicitly modeling carbon balances associated with deforestation and both direct LUC and ILUC, demonstrating that prioritizing degraded land for expansion can substantially reduce emissions. Additional research across the region shows that second-generation or waste-based pathways, such as biodiesel from waste cooking oil, generate stronger mitigation outcomes while avoiding land-use pressures [21], [27], [28], [32].

In contrast, SD applications in the ROW more often evaluate emissions through external assessment frameworks or sectoral indicators, rather than embedding full carbon dynamics within the SD structure itself. In the United States, for instance, the BSM focuses on market and industry dynamics while emissions are assessed through linked LCA workstreams that evaluate Renewable Fuel Standard scenarios [12], [15]. Similar approaches are recommended in Canada, where coupling SD models with environmental and social LCA allows emission indicators to function as feedback influencing investment decisions [20]. Some European studies go further by explicitly modeling above- and belowground carbon stocks to estimate annualized LUC emissions consistent with sustainability policies such as RED-II [8].

Other ROW applications incorporate emissions through technological comparisons or sector-specific modeling. For example, studies in South Africa compare process configurations and show that biomass-based heat supply for ethanol production can reduce emissions by approximately 63% relative to coal-based systems [30]. In Indonesia and India, emissions are incorporated into SD structures through fuel-production nodes, LUC dynamics, or transportation-sector fuel mix simulations [18], [29]. Overall, the comparison indicates that LA studies tend to integrate emissions more directly with LUC and resource governance, whereas ROW models frequently assess climate impacts through LCA linkages, technological pathway comparisons, or sector-level indicators, reflecting different regional sustainability priorities within SD biofuel research.

2.2.3. Financial modeling in sustainability

Economic and financial assessment is commonly integrated into SD biofuel models to represent how prices, incentives, and profitability evolve and shape industry behavior over time. LA studies add a distinct economic emphasis; they more often make the economic dimension inseparable from land dynamics and social repercussions. Studies suggest that strategies for sustainable expansion are possible and financially viable [26]. In Colombia, SD modelling has explicitly examined how increasing biofuel demand can create pressure for land expansion and food security [19]. Other LA regional models similarly treat demand as the production pull, but demand remains dependent on feedstock availability and price; as acquisition rates rise, prices rise [22]. In other cases, profitability is linked to production capacity and feedstock supply capacity, showing how rising production costs reduce profitability and output, while revenues from co-products can offset cost pressures [23]. Investment is also modeled as an endogenous mechanism that improves productivity and expands production. Beyond plant economics, feasibility assessments in the region also consider other economic dynamics, such as Gross Domestic Product (GDP) contributions, additional revenues, and export markets. Finally, in contexts where governments control fuel and biofuel prices, these prices are often treated as exogenous parameters, and the model is oriented to policy analysis on how incentives affect producer profitability [24].

Across the literature in the ROW, industry expansion is depicted as investment-dependent, in which profitability, shaped by costs, prices, and policy, feedback into production capacity growth [7]. Contrary to LA, in these cases, demand is usually treated as the primary pull for production, and when combined with subsidies, incentives, credits, or tax exemptions, it raises expected profitability and unlocks investment [6]. Mandates are often used to stabilize demand by tying biofuel volumes to renewable volume obligations linked to fossil fuel consumption [17]. Yet mandates alone are insufficient to trigger sustained expansion; market uptake is also modeled as dependent on fossil fuel consumption patterns and public acceptance. The economic stability of a biofuels project depends on predictable policy instruments; volatility in policy or market conditions discourages investment and can suppress long-term growth [7].

LA and ROW use production cost as part of the financial evaluation; however, ROW primarily analyzes the system through profitability. Profitability is often measured using the Internal Rate of Return (IRR) or the Net Present Value (NPV) to support investment decisions [30]. In those models, the key drivers of profit are consistently structural: feedstock costs, transportation costs, capital costs, and fixed and variable operating costs [14]. Feedstock price is emphasized not only because it dominates production costs, but also because it is the main link between economics and competition over land and other uses. Physical constraints may limit expansion even when market opportunities exist and promote economic growth, making profitability an endogenous outcome rather than an assumed condition. Incentives are also included in the economic analysis; they can target technology development, reduce capital investment, subsidies, or support for downstream blending and distribution [15]. These are applied in isolation or combination, and show that they not only shift a single cost but also change whether investment feedbacks become self-reinforcing or remain volatile [6].

2.3. Policy approach in modelling

Across the SD models in LA and ROW, policy assessment is central because policies shape the feedback structure that drives adoption, investment, and long-run industry stability. In LA, policy assessment tends to foreground land constraints and government market structures. A study in Colombia showed that a well-designed policy can stabilize markets and generate benefits for both biofuels and land outcomes [19]. Other work emphasizes government control and support as major determinants of production cost and capacity, concluding that policy is required to increase blending mandates and expand production capacity [23]. LA policy levers also extend beyond fuel policy into land sustainability targets, such as reforestation or zero-deforestation goals; these are integrated into dynamic models, and the results showed a simultaneous increase in reforestation, preserve productive lands, and support biofuel production under a sustainability approach [26]. Some models evaluate policy explicitly against sustainability targets that include demand, LU, water efficiency, and employment, showing that policy intervention is necessary to keep systems within desired sustainability goals [25].

In ROW, policies are studied as mechanisms to create or stabilize demand, either through mandates, incentives, or subsidies focused solely on closing the price gap between biofuels and conventional fuels [17]. More broadly, subsidies are used in the models to sustain profitability, attract investment, and maintain growth trajectories, consistent with the argument that growth emerges through profitability-driven investment enabled by demand pull created by regulations and fiscal support [6]. Related work suggests that if governments aim to subsidize the cost gap between biofuels and petroleum fuels, support mechanisms should be adaptive to market demand conditions and technology improvements rather than remain fixed parameters [31]. Other studies show that biofuel projects can require unrealistically high subsidies to become profitable, questioning the applicability of this strategy and motivating deeper analysis of the implications of subsidies across other aspects of the SC [30].

In LA as well as in ROW, policies are tested through scenario and sensitivity analyses [33]. In many cases, policies enter as exogenous scenario switches ("what-if" scenarios), and the model is used to compare outcomes across fixed policy packages [6]. The value of scenario testing depends on how feasible the strategies proposed are. The existing policy and regulatory landscape should first be assessed and then translated into scenarios to propose achievable goals [14]. Literature differs in evaluation criteria; in ROW, policies are assessed mainly through producer profitability and growth responses [6], whereas in LA, policies are evaluated through broader sustainability criteria and multidimensional outcomes [19], [23], [26].

A recurring limitation in both models in ROW and LA is the lack of full integration of the cross-effects among policy, environment, and investment dynamics, which constrains their ability to evaluate policy packages that must work simultaneously across domains. Policies that remove barriers across the entire system tend to outperform policies that are only focused on one segment and neglect the others [15]. In general, policy studies in the biofuel industry require a holistic view of coupled feedstock production and distribution, technology developments, and economic assessment.

3. Reflections

Lesson 1: Transition Optimization vs. Structural Viability in Biofuel SC Modeling

In LA contexts, the emphasis of SD biofuel SC modeling often centers on structural viability rather than transition optimization. The primary concern is whether the system can sustain and scale over time. Models explore whether land and feedstock supply can expand without disrupting food systems, whether investment cycles remain stable under policy volatility, whether infrastructure bottlenecks emerge, and whether expansion is financially resilient. A critical structural feature in many LA countries is the role of the state as a primary buyer or price stabilizer through blending mandates, fixed pricing schemes, or direct market participation. As a result, biofuel markets are frequently policy-driven, and the stability of government programs becomes a central component of system behavior.

In contrast, much of the SD literature for ROW assumes an industry that is already structurally mature. Fuel markets are typically deeper, private capital plays a larger role, and policy signals tend to be more predictable. Consequently, the modeling focus shifts toward transition optimization. Researchers examine how to improve cost competitiveness relative to fossil fuels, accelerate carbon reduction pathways, incorporate technology learning curves, evaluate the effects of blending mandates on market shares, and assess system behavior under long-term decarbonization targets. In these contexts, the structure of the industry is largely taken as given, and the primary challenge becomes optimizing the transition within an established energy system.

Lesson 2: Limited integration of social actors as endogenous decision-makers in biofuel SC models

Comparing LA and ROW, social dimensions in biofuel SC models are typically represented endogenously through individual actors or community-level decision-making processes rather than through sector-level indicators. In the reviewed LA studies, the most common social indicators include rural development, food security, economic growth, energy security, and employment generation, which are generally modeled as system outcomes arising from production expansion, changes in land allocation, or increased investment in biofuel infrastructure. These indicators are often incorporated through explicit behavioral modeling of actors within the SC rather than through macro-level feedback loops linking agricultural production, biofuel output, and national economic indicators.

In the LA context, this modeling choice is particularly significant. In many countries in the region, the agricultural sector represents a structurally important component of the national economy, and farmers are frequently organized through cooperatives, associations, or unions. In several cases, producers are also landowners, meaning that land allocation decisions are not purely market-driven or centrally dictated by policy but are influenced by collective farmer decision-making processes. However, the ROW literature reviewed does not commonly model farmers as endogenous agents whose expectations, risk perception, or collective organization influence feedstock supply dynamics. Instead, land allocation is often treated as a responsive stock that adjusts mechanically to price or policy signals. This creates a structural simplification. In practice, the configuration of the biofuel SC in parts of LA may follow a sequence as shown in Figure 3.

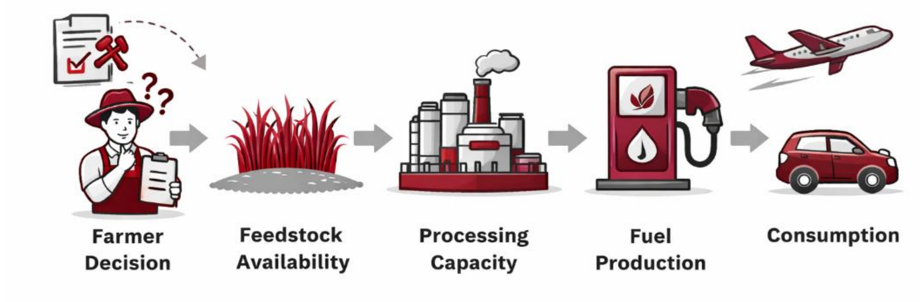

Figure 3. Biofuel SC considering social actors as part of the value chain

Treating farmers and producer associations as endogenous components of the SC would allow the incorporation of behavioral feedback, such as responsiveness to targeted incentives, resistance to land conversion, or collective negotiation effects. In such a configuration, policy instruments directed toward farmers, including crop-specific incentives or support mechanisms, may produce different dynamic responses compared to instruments targeting downstream producers, such as tax credits or refinery subsidies. Integrating these social actors into the model structure would therefore shift the representation of the SC from a production-centered system to a decision-centered system, better reflecting contexts where agricultural organization plays a significant role.

Lesson 3: Land Allocation, Resource Constraints, and Sustainability Trade-offs in Biofuel Systems

A comparison between LA and ROW SD applications reveals both shared methodological patterns and important contextual differences in how sustainability dimensions are represented. In LA, land is commonly modeled as a central driver shaping biofuel expansion and sustainability outcomes. Many studies explicitly simulate land allocation across competing uses, such as food crops, livestock, biofuel crops, forests, and degraded land, highlighting the role of land governance, food–fuel competition, and LUC in determining system performance. In contrast, ROW studies often treat land primarily as a structural constraint on feedstock availability or production capacity, typically represented through bounded land stocks or allocation mechanisms linked to prices and productivity rather than through detailed land governance dynamics.

Water remains the least integrated sustainability dimension in both LA and ROW SD studies. In LA, some models, particularly in Brazil and Colombia, attempt to represent water demand, scarcity, or pollution associated with biofuel production. However, many studies still treat water indirectly or omit it from the core system structure. In ROW, water is more commonly acknowledged as an important resource but typically appears as a cost parameter or contextual factor rather than as a dynamic constraint within feedback loops. Compared with land and GHG emissions, water is rarely modeled as an endogenous stock subject to depletion or competition. This limitation indicates that future SD frameworks should systematically incorporate water availability, irrigation demand, pollution flows, and water-energy -land interactions in order to strengthen the sustainability assessment of biofuel transitions.

Regarding GHG emissions, LA models frequently connect climate outcomes to LUC processes and feedstock pathways. Studies in countries such as Colombia and Brazil show that deforestation, ILUC, and agricultural expansion can significantly influence carbon balances, sometimes offsetting the benefits of fossil-fuel substitution. These models emphasize that mitigation outcomes depend on land management, productivity improvements, and the use of degraded land or waste-based feedstocks. In ROW applications, emissions are incorporated through a broader range of approaches, including coupling SD models with LCA frameworks, modeling carbon stocks and LUC, or evaluating technological pathways. In many cases, emissions function primarily as performance indicators linked to policy targets rather than as drivers embedded within land-SD.

Lesson 4: Same economic dynamics, different boundaries

Across the literature, the economic dimension revolves around a shared growth mechanism; profitability shapes investment, investment builds capacity, and capacity affects supply, prices, and future profitability. In this sense, LA studies do not depart from the global SD approach; many use the same fundamental levers (prices, incentives, costs, and capacity expansion) and the same endogenous logic linking profitability to growth. However, the difference appears in the system boundaries and economic relationships that the authors choose to emphasize. These LA models more frequently embed economics inside the land-food-fuel linkages, and economic outcomes are tied to land allocation, food price responses, and sustainability trade-offs that become binding constraints rather than externalities. This shifts the economic reflection from de-risk investment strategies toward creating economic expansion without affecting sustainability, and how feedbacks can limit feasibility or create resistance.

In several LA cases, prices are treated as exogenous, reflecting regulated markets, which can reduce endogenous price dynamics compared to studies in liberalized markets. Overall, a fair reflection is that LA's economic modeling has broadened the economic lens to incorporate coupled land, rural development, and food dynamics, but it has not consistently distinguished financial structuring from the international literature. Both literatures still lack the inclusion of real economic mechanisms, especially financing opportunities, capital market constraints, and political stability.

Lesson 5: Policy assessment converges around scenario testing of mandates and incentives

In LA, policy success is measured against land constraints and social-environmental trade-offs, in contrast to ROW, which focuses primarily on closing the cost gap between biofuels and fossil fuels to spur investment. However, SD policy assessment converges on similar tools and levers. Policy assessment methodology in biofuel models looks broadly similar across regions. Policies are evaluated through scenario and sensitivity testing, where mandates, credits, subsidies, or tax instruments are introduced as what-if scenarios, and the model is used to compare system responses over time. In LA and ROW, results show that policies are most effective when they remove barriers across the whole system rather than targeting a single bottleneck while neglecting others. At the same time, models frequently imply that some policy designs would require levels of support that may be politically or fiscally unrealistic, suggesting that the feasibility and durability of policies matter as much as technical effectiveness. Where LA applications may differ is in what is considered a "successful" policy; rather than focusing primarily on closing the cost gap to trigger investment, several studies place greater weight on land constraints and social-environmental trade-offs. SD policy assessment converges on similar tools and levers, while in LA context shifts, and constraints dominate project feasibility.

Based on these lessons, **Figure 4** presents a causal loop diagram that positions the biofuel SC at the core of the analysis, from land allocation and feedstock production to conversion, distribution, and end use. Three sustainability dimensions, environmental, social, and financial, are embedded around that chain. In the social dimension, the diagram addresses a recurring gap in the literature by representing the farmer's decision-making as an endogenous driver of feedstock supply. Adoption and crop conversion respond to interacting parameters, including food security concerns, land availability, rural development expectations, profitability, perceived market opportunities, and policy signals. On the environmental side, the diagram includes water use, which is a recurrent omission in SD biofuel SC models. For water-intensive pathways such as sugarcane, water demand can become a binding constraint on feasibility expansion; therefore, it should be represented as an endogenous limiting factor. Finally, the diagram represents policy as exogenous levers distributed across the full SC, affecting land conversion incentives, the viability of production and processing, and downstream blending and use. Policy is not treated as a single point intervention but as a set of levers applied across the full SC.

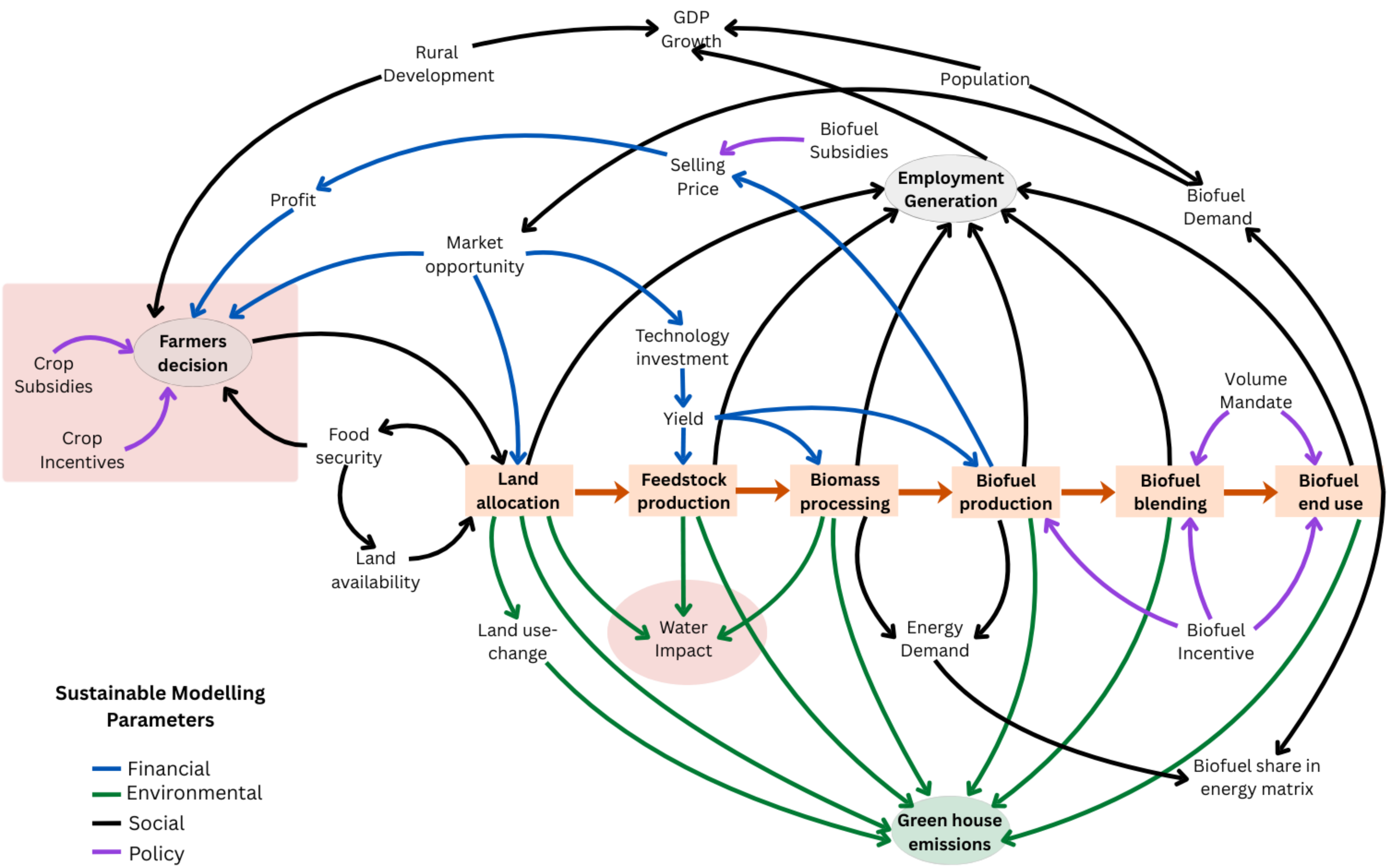

Figure 4 Causal Loop Diagram for a Biofuel Supply Chain Incorporating Policy Factors and Economic, Environmental, and Social Sustainability Parameters

4. Conclusions

The review of SD applications in biofuel SC modeling reveals that, while similar methodological structures are used across regions, the emphasis of the models tends to differ between LA and ROW. In LA studies, SD models often focus on structural viability, examining whether biofuel systems can scale under constraints related to land availability, feedstock supply, investment stability, and policy credibility. These studies frequently incorporate stronger government participation in the system through mandates, price stabilization mechanisms, or direct market intervention. In contrast, ROW models more commonly assume mature markets and focus on transition optimization, emphasizing cost competitiveness, technology learning, and emissions reduction pathways. However, this distinction should not be generalized, as the available literature remains relatively small and heterogeneous, and the observed differences reflect tendencies rather than a clear regional divide.

From a sustainability perspective, SD models worldwide consistently address environmental emissions. LA studies more often incorporate LU dynamics and food–fuel interactions. However, water consumption remains poorly integrated across both contexts, despite its relevance for agricultural biofuel systems. Similarly, the social dimension is weakly represented in most studies. Social variables such as employment, rural development, or economic growth are typically modeled as macro-level outcomes rather than as endogenous actors influencing feedstock supply or land allocation decisions.

Overall, the literature suggests that future SD applications should move toward more integrated system representations. A comprehensive modeling framework would incorporate the interactions between farmers and land allocation decisions, feedstock supply, processing capacity, market demand, environmental constraints, and policy feedbacks. Developing a causal loop structure that explicitly connects these elements would strengthen the representation of sustainability trade-offs and better reflect the complex interactions between economic, environmental, and social dimensions within biofuel SCs.

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