Proceedings of the 2014 Industrial and Systems Engineering Research Conference
Y. Guan and H. Liao, eds.

A Review of Lignocellulosic Biomass and Biofuel Supply Chain Models

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Abstract

Biofuels have received considerable attention lately due to the scarcity of fossil-based energy and its adverse impact on the environment. Furthermore, the need for a consistent energy supply has led researchers and practitioners to investigate renewable sources such as biofuels and biomass. However, more investigation is needed, particularly for lignocellulosic (energy crops) biomass production and the biofuel supply chain. Various studies have been conducted to ensure the feasibility of biofuel and biomass production while maximizing its benefits, and to gain insights about energy generation from biomass-based sources. In this paper, we provide a literature review of the models developed for supply chain and production of lignocellulosic biofuel and biomass from energy crops, such as switchgrass and miscanthus. We also distinguish studies in terms of research area and methodology. Additionally, we compare three studies in detail with respect to the considered methodology, objective function, constraints, decisions taken, and application area. Finally, we provide a discussion of the areas where there is a research gap, and we highlight research needs in the biomass and biofuel supply chain area.

Keywords
Review, Supply Chain, Biofuel and Biomass, Lignocellulosic, Operation Research

1. Introduction

Renewable energy sources have gained growing importance due to concerns about the future of scarce energy sources such as fossil fuels along with the pressure of adverse environmental impacts of traditional fuels. Biofuel, an alternative to conventional energy sources, is considered a type of sustainable energy that can replace oil. In order to produce biofuel, biomass is processed in biorefineries. In general, biomass refers to all types of plants and materials from plants, including forestry, agricultural resources such as food and cellulosic crops, or even animal waste. Bioenergy is a general form of biomass-based energy used for purposes such as electricity and heating. Therefore, biofuel is a subsection of bioenergy and refers to energy as fuel derived from biomass [1].

Biomass is a sustainable energy source with a great amount of supply potential. It is also environment friendly due to its benefits, such as prevention of soil erosion and reduction of CO_2 emissions. Considering low supply reliability and damages on the natural life of fossil-based sources, biofuel and bioenergy have turned into popular alternatives. Among the mentioned sources of biomass, lignocellulosic biomass is used to produce second-generation biofuel, whereas first-generation biofuel depends primarily on food commodity. Production of first-generation biofuel plants has already gone commercial, negatively impacting soil quality because these plants require large quantities of chemicals and fertilizers. On the other hand, lignocellulosic materials are typically cheaper. In addition, second-generation biofuels are proposed because of concerns relative to food shortage that may occur as a result of using food crops in energy production. However, technology is not developed enough to efficiently convert lignocellulosic biomass into biofuel. Therefore, investment in the biofuel industry raises the issue of profitability. In order to increase profitability, plenty of studies focus on the conversion technology that will increase the output and decrease the cost of biofuel production from lignocellulosic biomass [2]. However, in order to make the investment in biofuel industry economically feasible, efficiency issues regarding biomass production and biofuel supply chains need to be considered.

In this paper, we review studies about biomass production and biofuel supply chain, particularly for lignocellulosic (energy) crops. In section 2, we explain our approach and categorization of the reviewed papers. Here we provide a list of studies along with the models used and related areas. In section 3, we present the papers in various areas that have deterministic models, while in section 4, we review the probabilistic models in the biomass production and biofuel supply chain. In section 5, three selected articles are analyzed in detail and a comparison is conducted. In section 6, discussion of the main findings of the literature review and concluding remarks are provided.

2. Overview of Literature Review

A number of studies deal with biomass production at the farm level and supply chain of biofuels. Research conducted in the biofuel and biomass area changes from deep analyses to strategic decisions at the managerial level. In order to systematically cover the literature, we have classified studies according two main perspectives: modeling and research area. Based on the literature review, modeling studies are classified into two groups—as deterministic models and as probabilistic models. Probabilistic models have three categories, while deterministic models have two categories. There are also three different categories under the research area. All of this is displayed in Figure 1 below.

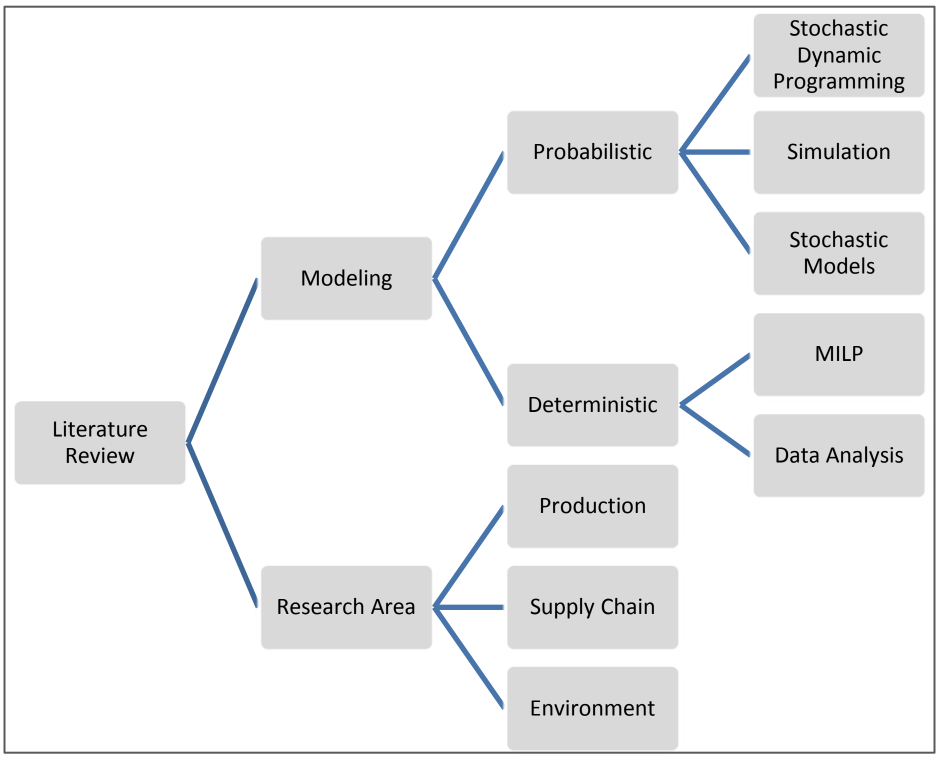

Figure 1: Classification of papers in this review

Before introducing the studies covered in this study, we need to draw attention to the literature review study regarding the supply chain of petroleum-based fuels and biofuels [3], which focuses on the supply chain and decision levels such as strategic, operational, and tactical. However, we have a different review approach in this paper. First, we primarily focus on the biofuel supply chain, particularly from lignocellulosic biomass. Our review also involves studies of biomass production at the farm level. Second, we categorize the articles based on the considered research area: production, supply chain, and environment. Our purpose in this paper is to expand knowledge by classifying papers in the literature relative to cellulosic biomass and the biofuel supply chain. By doing so, we aim to discover those areas where there is a lack of investigation and a need for further attention from researchers.

Here we have reviewed a total of 33 studies, which, as mentioned previously, are classified according to methodology used and the area in which they are applied. We primarily include studies dealing with energy crops and their production. The reviewed articles are listed in Table 1 below.

Table 1. Classification of studies covered in this review

Paper (Year)	Method					Research Area		
	Deterministic		Stochastic					
	MILP	Data Analysis	Dynamic Programming	Simulation	Stochastic Models	Production	Supply Chain	Environment
Thomason et al. [4] (2004)		X				X		
Sokhansanj et al. [5] (2009)		X				X		
van Dama et al. [6] (2009)		X				X		
Duffy and Nanhou [7] (2002)		X				X		
Duffy [8] (2008)		X				X		
Elbersen et al. [9] (2005)		X				X		
Haque and Epplin [10] (2010)	X					X		
Papapostolou et al. [11] (2011)	X						X	
Freire et al. [12] (2004)	X						X	X
Kim et al. [13] (2010)	X						X	
You and Wang [14] (2011)	X						X	X
An et al. [15] (2011)	X						X	
Wetterland et al. [16] (2012)	X						X	X
Love et al. [17] (2011)		X						X
Holguin et al. [18] (2010)		X						X
Ceotto [19] (2009)		X						X
van Dama et al. [20] (2009)		X						X
Roth et al. [21] (2005)		X						X
Murray et al. [22] (2003)		X						X
Clancy et al. [23] (2012)				X		X		
Osmani and Zhang [24] (2014)					X		X	
Sharma et al. [25] (2013)				X	X		X	
You [26] (2013)					X		X	
Awudu and Zhang [27] (2013)					X		X	
Xie et al. [28] (2014)	X						X	
Dal-Mas et al. [29] (2011)			X				X	
Sokhansanj et al. [30] (2006)			X			X	X	
Khanna et al. [31] (2011)			X	X		X	X	
Zhang et al. [32] (2012)				X			X	
Mobini et al. [33] (2011)				X			X	X
Cobuloglu and Buyuktahtakin [34] (2013)	X					X	X	X
Akgul et al. [35] (2012)	X						X	
Zhang et al. [36] (2012)	X					X	X	

3. Deterministic Models

Deterministic models used for biomass production and a biofuel supply chain generally utilize optimization models, particularly mixed-integer linear programming (MILP). There are also various data analysis studies such as estimation, data collection, and field experiments. Studies that propose a deterministic model for lignocellulosic biomass and biofuel supply chain are reviewed based on the areas they investigate.

3.1 Studies on biomass production

Increasing biomass yield amount from a given area is generally a primary concern in many studies in agriculture. Studies regarding the biomass production from cellulosic crops have various perspectives. Some studies conduct experiments in order to analyze the effects of fertilization, harvesting time, and frequency on yield amount. One of these is performed by Thomason et al. [4] to determine the response of switchgrass to the application of different amounts of nitrogen (N) as fertilizer and to various harvesting frequencies. They develop scenarios and conduct field experiments in central Oklahoma. Their findings indicate that, in order to maximize the harvested amount, multiple harvesting in a year should be done. They claim that the amount of N does not affect the yield amount. On the other hand, multiple harvesting shows side effects such as decreasing the life cycle of switchgrass, which reduces the total yield. Several data collection studies clearly define the cost of various farm operations. One of these studies conducted by Sokhansanj et al [5] defines the cost of production, yield per hectare, energy input cost, machinery, and transportation cost of switchgrass. It also provides costs with respect to changing amount of switchgrass yield per hectare. Similarly, but more comprehensively, Dama et al. [6] discuss a large-scale cost estimation and economic analysis study for Argentina based on switchgrass and soybeans production. Supply chain options and production locations are evaluated under different scenarios according to the estimated cost and yield rates. Duffy and Nanhou [7] develop different scenarios with various seeding seasons, cultivation land, and machinery types to estimate cost of switchgrass production per hectare in the state of Iowa. They make some assumptions to determine those values and indicate that the major factors affecting the cost are yield and land charge. The goal of their study is to be able to show the profitability of producing switchgrass. Another study to estimate the cost is performed by M. Duffy [8]. This particular study also includes the storage and transportation cost estimation in addition to switchgrass production cost. A study conducted in Europe by Elbersen et al. [9] on the potential yield of perennial grasses analyzes and estimates the yield amount of switchgrass and miscanthus.

Different than the mentioned studies in terms of methodology, Haque and Epplin [10] minimize the cost of switchgrass production by using the MILP model. They also include the transportation cost from biomass to refinery by evaluating the optimal harvesting strategies of production amount, fertilization N, and transportation modes.

3.2 Studies on supply chain

A considerable number of studies in the literature cover the biofuel supply chain. In one, Papapostolou et al. [11] propose a mathematical model for a supply chain of biofuels that integrates both economic and technical parameters. The performance of the supply chain, which includes suppliers, storage facilities, transporters, and a number of retailers, is affected by those parameters. MILP is used to formulate the problem, which includes only major operational constraints to have a solvable problem model. The authors do not consider cellulosic biomass in their study. On the other hand, Freire et al. [12] propose a mathematical model that considers both economic and environmental consequences of biofuel production. They use a life-cycle assessment framework and partial equilibrium microeconomic model while establishing a multi-criteria linear optimization model. In this study, they consider dedicated energy crops such as sugar beets, wheat, and rapeseed. The model is applied to a biofuel production case study in France. Similar to that research, Kim et al. [13] investigate the value chain, starting from biomass sources, such as forestry, and ending at the final markets. Locations of biomass, conversion sites, logistics locations, the amount of products that should be transported, capacities, and technologies that are used in those facilities are decided according to the proposed MILP model. The objective function of the model is to maximize overall profit by submitting the cost from revenues.

In addition to the previously mentioned studies, life cycle assessment is investigated as a core subject of biofuel supply chain in research by Fengqi and Belinda [14]. They propose a MILP model by considering environmental impacts of the supply chain such as greenhouse gas (GHG) emissions along with the economic impacts. However, they do not primarily consider energy crops as the biomass source. A multi-objective, multi-period, MILP model is proposed that minimizes the cost. The model defines the locations and number of transportation facilities, amounts to be transported, technology in the facilities, and inventory amount. In figure 2 below, the scope of that research is presented, which is also the scope of this literature review.

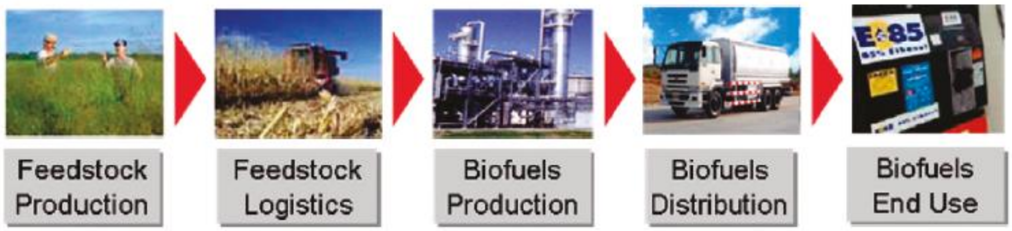

Figure 2. Flow of Biofuel Supply Chain from Feedstock Production to Biofuels End User [14]

There are also supply chain studies that maximize profit, which is also studied by An et al. [15]. They claim that their model is the first one dealing with all steps of the two-directional biofuel supply chain. Using a time-staged deterministic model, their model determines the storage amount of the biomass, technology used, and warehouse locations. On the other hand, Wetterlund et al. [16] minimize the cost of the entire supply chain system from production plant to fossil fuel transportation. They involve lignocellulosic crops in their study and consider CO_2 emitted during transportation.

3.3 Environment studies

In the literature, there are various studies related to environmental effects of producing second-generation crops. While most of them investigate the effects of producing and harvesting practices on biological diversity, very few deal with hazards to wildlife and human life. One of the recent studies dealing with the risks to human health and wildlife associated with bioenergy crop production on a large scale is done by Love et al. [17]. They investigate the threshold toxicity levels of fertilizers on the health of a bluegill fish species and also humans by using a Soil and Water Assessment Tool. Another study is done by Holquin et al. [18] to determine the effects of switchgrass-based biomass crop production on insect diversity in South Carolina. After three years of data collection and sampling, abundant species in various regions and at various times of the year are identified. It is indicated that biodiversity is adversely affected if high-density fertilization is implemented on the field. Ceotto [19] finds that when there is grazing, a variety of species increases in the long term. He also analyzes the negative effects of biomass production on grassland. Dama et al. [20] convey a large-scale study for environmental effects of switchgrass- and soybean-based bioenergy production. They consider environmental effects such as reduction in GHG emissions, change in carbon stock, soil erosion, and water quality. They present the results of each sustainability principle analyzed according to changing scenarios.

Two similar studies focus on the effects of farm operations on animal population, particularly the change in grassland bird population. In one, Roth et al. [21] investigate the bird diversity and population with respect to harvesting times and methods. They collect data for five years in Iowa for different harvesting scenarios to analyze their effects on bird population. They suggest shifting the harvesting area as a harvest management to support different kinds of bird species. In the other study, Murray et al. [22] explore the effects of converting marginal lands to switchgrass-based biomass production fields. The abundance of bird species increases in Iowa based on their estimation by using a Geographic Information System (GIS).

4. Probabilistic Models

This section includes all studies that utilize probabilistic models for biomass production and the biofuel supply chain. Uncertainty, such as the yield amount and price fluctuations involved in biomass and biofuels, has also been studied by many researchers. For example, Clancy et al. [23] investigate the financial risk associated with biomass production. In order to calculate the net returns of biomass crops such as miscanthus, they propose a stochastic budgeting model. They determine that miscanthus is less risky than willow to produce in Europe. Osmani and Zhang [24] maximize the profit of lignocellulosic biofuel supply chain by proposing a two-stage stochastic optimization model. They also simultaneously minimize carbon emissions. It is shown that financial and environmental benefits decrease as uncertainty increases. Sharma et al. [25] develop a stochastic integer optimization model in order to maximize the net return of the technological investments. They also utilize Monte Carlo simulation to quantify the return of investment. You [26] also proposes a stochastic MILP in order to minimize the annualized cost of the supply chain while deciding the network design. Biomass seasonality and demand uncertainty are considered during the decision making. The proposed models are applied to two case studies in the state of Illinois. Similarly, in order to maximize profit, Awudu and Zhang [27] propose a stochastic linear programming model utilizing Benders decomposition technique and applying the model in North Dakota. Another study by Xie et al. [28] proposes a mixed-integer programming model in order to minimize the lignocellulosic biofuel supply chain. Feedstock supply is considered as the uncertain parameter in the model development. Tactical decisions along with strategic decisions, such as location of the facility, are optimized.

Dynamic programming studies have also been done in the biofuel supply chain area. Dal-Mas et al. [29] propose a dynamic MILP model to minimize the financial risks of investment. Price of the biomass source, which is corn, and selling price of the biofuel are considered in the model development. They demonstrate the model's applicability of with a case study in Italy. Sokhansanj et al. [30] propose a dynamic programming model for operational-level decisions for biomass supply and logistics. Their model includes dry matter loss and weather conditions, which affect moisture content. A case study on corn stover is presented for applying the model. In addition to dynamic programming, some researchers use simulation to analyze the biofuel supply chain. Khanna et al. [31] incorporate a simulation model with a dynamic, nonlinear mathematical program in order to design the biofuel supply network. They allocate two land types for the production of cellulosic crops such as wheat straw, switchgrass, miscanthus, and corn stover under various cost scenarios. Zhang et al. [32] develop a simulation model as a management tool in the biofuel supply chain. They decide on facility location, inventory, and logistics design while considering GHG emissions as a performance criterion. They also include harvesting, transportation, and storage in their simulation model. In a similar manner, Mobini et al. [33] develop a simulation model for the forest-based biomass. They define the cost of logistics by also analyzing the CO_2 emitted during the supply chain. However, in this model, biomass is used for power generation instead of biofuel production.

5. Comparison of Three Selected Studies

In this section, we review three recent research papers involving MILP models for lignocellulosic biomass production and biofuel supply chain: Cobuloglu and Buyuktahtakin [34], Akgul et al. [35], and Zhang et al. [36]. In these papers, models are applied to a case study in order to show the applicability of the proposed method developed.

Before comparing these papers, we explain the studies in terms of some particular features, which can be listed as methodology, objective function, decision variables, and constraints included in the model, as well as the application area and contributions of the paper.

Features of the first study [35] are as follows:

- An MILP model is used for the economic optimization of a UK advanced biofuel supply chain.
- The objective of the study is to minimize total supply chain cost, which includes the cost associated with investment, production, transportation, and outsourcing biomass and biofuel.
- Decision variables can be considered as strategic decisions, which involve location of biofuel facilities, biofuel production rates, and location of biomass cultivation. They also decide on some tactical-level decisions such as transportation mode for biomass and biofuel, biomass imports, and biomass cultivation rate.
- The mathematical model has demand constraints, production constraints regarding biofuel production and biomass cultivation, a sustainability of food production constraint that avoids competition between food and biomass, and transportation constraints.
- The proposed model is applied on a UK-based hybrid first/second-generation biofuel supply chain study. The UK has been considered by discretizing it into 34 cells, where each region can include a couple of cities.

Features of the second study [36] are as follows:

- An MILP model is proposed for the integrated optimization of a switchgrass-based bioethanol supply chain.
- The objective of the study is to minimize the total switchgrass-based bioethanol supply chain cost by including various cost components such as rental cost, cultivation and harvest cost, storage cost, transportation cost of biomass and ethanol, and fixed cost of biorefineries and facilities.
- Decisions made in this MILP model include allocation of switchgrass to marginal lands, harvest method, location of preprocessing facilities and biorefineries, capacity of biorefineries, material flow from supply zones to biorefineries, and production volume of biorefineries.

- The model involves capacity constraints such as land availability for cultivation and biorefinery capacity, and material flow constraints regarding biomass and biofuel transportation.
- The model is applied in North Dakota and involves all of its 53 counties in the case study.
- The proposed model only considers marginal land for switchgrass cultivation, which strictly avoids competition between energy and food crops on cropland. Three different harvest methods are considered for switchgrass.

Features of the final study [34] are as follows:

- An MILP model is utilized for the economic and environmental analysis of biomass production.
- The model maximizes the economic value obtained from switchgrass production by considering economic and environmental benefits such as sales of biomass, savings from soil-erosion reduction, and the decrease in CO2 emissions.
- Optimal decisions involve the allocation of zones to biomass cultivation, seeding method, harvesting time and locations, amount of switchgrass to be produced in each zone at each year, budget allocation for seeding, production, harvesting, and transportation operations.
- The model includes production constraints regarding the growth of switchgrass and its harvesting, a budget constraint that allocates the total budget to various farm operations, and environmental constraints that involve the sustainability of bird populations and food production.
- The model is applied in Hugoton, a city in southwest Kansas, by discretizing it into 441 cultivation zones, where each zone is one square mile.
- The study involves deciding on various seeding scenarios. The environmental benefits of switchgrass cultivation are also considered. Cropland and grassland along with the marginal land are also involved in the model.

All of these studies use the MILP model for problems in biomass production and the biofuel supply chain. Although the application region changes from a whole country to a state and even to a city, they all include some strategic- and tactical-level decisions. Akgul et al. [35] mostly focus on the supply chain of biomass and biofuel, while Zhang et al. [36] involve some farm-level decisions on biomass cultivation. However, Cobuloglu and Buyuktahtakin [34] emphasize biomass production at the farm level by including the environmental outcomes.

All papers are summarized and compared in table 2 below, which shows the similarities and differences among the three recent papers that have been studied for lignosellulosic biomass production and biofuel supply chain.

Table 2: Comparison of three studies

Features	Paper-1, [35]	Paper-2, [36]	Paper-3, [34]
Method Used	MILP	MILP	MILP
Objective of Study	Minimize supply chain cost	Minimize supply chain cost	Maximize revenue from biomass production
Decision Level	Mostly strategic decisions	Strategic and operational decisions	Mostly operational decisions
Application Area	UK	North Dakota	Hugoton, Kansas
Novelty	Lignosellulosic biofuel and food security	Integration of operational and strategic decisions	Integration of economic and environmental impacts of biomass production on all land types

6. Discussion of Future Research and Conclusion

In this paper, we review articles in the literature regarding second-generation bioenergy and biofuel crops. Our paper classifies the studies done so far in terms of research areas, such as production, supply chain, and environmental. At the same time, we cluster the articles in terms of the methods, including deterministic and probabilistic models. In addition, we identify future areas that require further investigation. This literature review may help researchers by providing them with a general overview of the studies conducted in biomass and biofuel supply chains of energy crops.

A histogram with respect to integration of methodology and research area is displayed in Figure 3. It helps to determine the missing combination of methods and areas to be investigated in the future. As shown, the majority of studies focus on the supply chain and MILP models. There are also a considerable number of studies regarding data analysis in the fields of environmental studies and biomass production. However, few simulation and probabilistic models are developed in order to analyze the environmental effects of biomass and the biofuel supply chain.

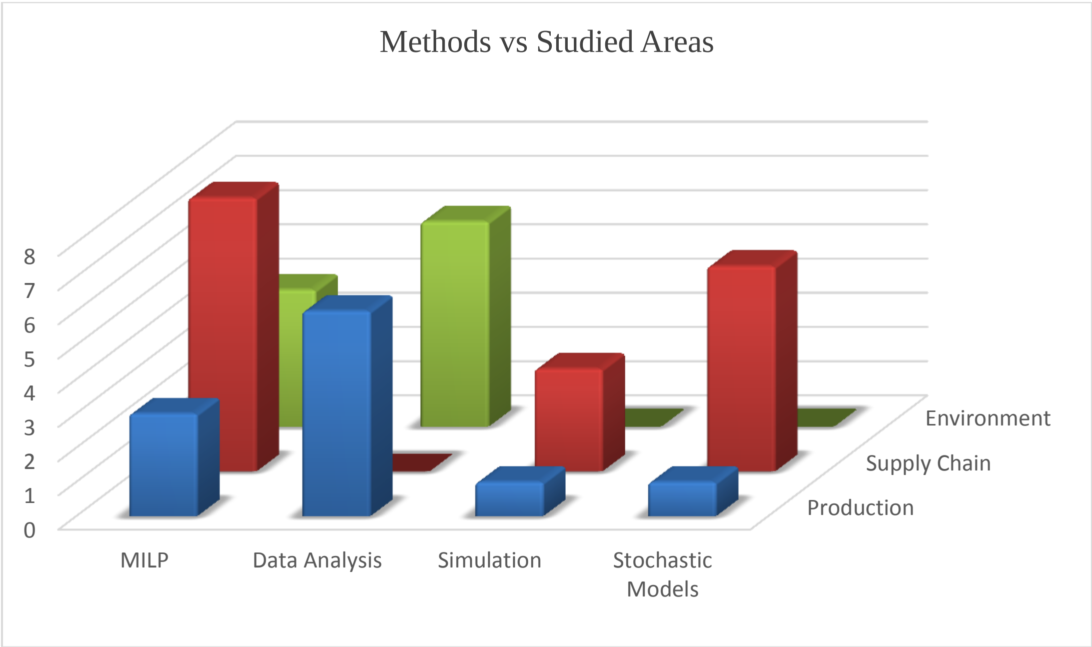

Figure 3: Deployment of reviewed studies

We have seen that studies on biomass production focus on the cost of production operations at the farm level. Many researchers conduct field experiments or make data calculations in order to define values of the parameters such as yield amount, transportation cost, fertilization requirement, and production cost. Studies on the supply chain of biofuels generally utilize MILP models to design the network and make optimum decisions. Some of them also consider environmental effects of the biofuel supply chain. On the other hand, most studies on environmental analysis depend on data analysis, particularly field experiments. Environmental aspects are included in some MILP models. There is a need for studies that particularly optimize the environmental outcomes. For example, we have not encountered any studies in our literature review that use mathematical models to restrict fertilization amounts or determine the effects of fertilization on the environment. When we review the stochastic models, we see that the majority of studies focuses on the supply chain of biofuel. There is also a need for studies that will combine the environmental analysis with stochastic models. Similarly, very few of the reviewed studies solve problems with respect to biomass production using stochastic models.

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