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Design of Biomass Value Chains that are Synergistic with the Food-Energy-Water Nexus: Strategies and Opportunities

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Abstract

Humanity's future sustainable supply of energy, fuels and materials is aiming towards renewable sources such as biomass. Several studies on biomass value chains (BVCs) have demonstrated the feasibility of biomass in replacing fossil fuels. However, many of the activities along the chain can disrupt the food-energy-water (FEW) nexus given that these resource systems have been ever more interlinked due to increased global population and urbanisation. Essentially, the design of BVCs has to integrate the systems-thinking approach of the FEW nexus; such that, existing concerns on food, water and energy security, as well as the interactions of the BVCs with the nexus, can be incorporated in future policies. To date, there has been little to no literature that captures the synergistic opportunities between BVCs and the FEW nexus. This paper presents the first survey of process systems engineering approaches for the design of BVCs, focusing on whether and how these approaches considered synergies with the FEW nexus. Among the surveyed mathematical models, the approaches include multi-stage supply chain, temporal and spatial integration, multi-objective optimisation and uncertainty-based risk management. Although the majority of current studies are more focused on the economic impacts of BVCs, the mathematical tools can be remarkably useful in addressing critical sustainability issues in BVCs. Thus, future research directions must capture the details of food-water-energy interactions with the BVCs, together with the development of more insightful multi-scale, multi-stage, multi-objective and uncertainty-based approaches.

Keywords: Biomass value chains (BVCs); food-energy-water (FEW) nexus; mathematical modelling; biomass supply chains; optimisation

INTRODUCTION

Rising concerns about climate change and sustainability have accelerated research efforts to seek alternative sources of energy [1]. The development of biomass as a low-carbon energy resource have been given much consideration as it can potentially contribute to the reduction of greenhouse gas emissions. Several life-cycle assessment studies show biomass as a carbon neutral resources [2]. The carbon dioxide footprint of biomass processes is often small or even zero because any carbon dioxide released during biomass processing is already considered captured from the atmosphere while the biomass is being cultivated [3]. Biomass resources include organic materials from plants and animals, such as: food crops; woody and grassy plants; forestry; agricultural residues; industrial and municipal solid waste; and animal manure and human sewage [4]. Through thermochemical or biochemical processes, biomass can be transformed into a variety of products ranging from energy and fuels to chemicals, materials and animal feed [5].

Research on biomass production and its conversion processes is well documented, especially under the concept of biorefineries [6]. The earliest mention on *multi-product biorefinery* dates back to 1999 as a challenge in bio-commodity engineering [7]. To date, 6170 Scopus-indexed articles in total (accessed on 14-09-2018) have been published on this topic with an average of 20% annual increase in the last 10 years. The attention placed on biorefinery research shows a big opportunity for its future deployment. However, the development of biomass supply chains and biomass value chains (BVCs) is crucial in achieving the true potential of biorefineries. Spatial and temporal factors are critical considerations in integrating components of the value chain. Components such as crop harvesting, biomass storage, conversion processes and transportation to end-users occur at different time and in different locations. Hence, truly efficient BVCs can be achieved when they continuously meet end-user demands while at the same time, smoothly operate the various processes involved [8]. Furthermore, when the environmental, economic and social impacts are managed in conjunction with spatial and temporal factors, sustainable BVCs can be attained.

Bioenergy and biorefineries have been linked to several sustainability challenges in maintaining a safe and healthy environment [9]. First, securing the feedstock for biorefineries and generating bioenergy require considerable amount of water for irrigation and energy for production of fertilizers. In addition, the cultivation of the feedstock will require additional land use that can compete with existing agricultural land; thus, posing a threat to food security. Second, more water and energy are needed to carry out many of the activities along the BVCs during the conversion and transportation processes. For example, water is an essential component for temperature control (e.g. heating and cooling) in power generation. Another example is the use of both fuel and electricity to power the biorefinery facilities as well as the cargo trucks and trains to and from industrial sites. These interactions between food, energy, and water systems are an important sustainability factor to consider in BVCs. Hence, the design of BVCs should strongly integrate the food-energy-water (FEW) nexus framework for more holistic systems-thinking policies.

Over the past ten years, reviews on biomass supply chains have been published to highlight key developments in the area of process design and development. The 150 review articles indexed in Scopus (accessed on 15-09-2018) focus on the logistic issues [10], storage issues [11], optimisation approaches [12], scale-up challenges [13], current progress on conversion technologies and its commercialisation [14] among others. Despite these, the insights from the current methodologies in designing BVCs in synergy with the FEW nexus have not been discussed.

Recently, Martinez-Hernandez and Samsatli [15] highlighted the importance of mathematical programming approaches in the design of biorefineries within the framework of FEW nexus. Given this motivation, the main contributions of this paper are the review and critical appraisal of the different optimisation tools for the design of BVCs in synergy with the FEW nexus.

The rest of the paper is organised as follows: The overview of BVCs is presented in Section 2; while its synergy with the FEW nexus is illustrated in Section 3. The review of mathematical tools for BVCs followed by analyses of its current progress are examined in Section 4. A separate review on the models for FEW nexus is provided in Section 5. The future directions are discussed in Section 6 and lastly, the summary and conclusions are communicated in Section 7.

BIOMASS VALUE CHAINS

Value chains play a significant role for the efficient and sustainable utilisation of biomass. They involve a network of technologies and infrastructure to convert low-value raw materials to high-value products. Activities such as biomass production (cultivation, harvesting and collection), resource conversion, transportation and storage make up the entire value chain of biomass. Meanwhile, the activities associated with these technologies and infrastructure include sourcing raw materials, processing, logistics, inventory management and waste management [16]. In this respect, BVCs are similar to biomass supply chains. However, a value chain problem involves determining a network that creates the most value by fully or partially satisfying the demands. On the other hand, a supply chain problem involves determining a network that always has to satisfy all of the given demands. In this review, value chains and supply chains are used interchangeably since their modelling is very similar (i.e. they involve the same set of activities) but the main difference is whether the satisfaction of demands is optional (value chain) or compulsory (supply chain). A schematic illustrating the activities in BVCs is shown in Figure 1. These are described as follows:

- **Harvesting and/or collection** – In general, the methods for harvesting and/or collection of biomass depend on its source. For example, cultivated crops for biofuel production such as sugar cane, corn, and coconut come from plantation fields. On the other hand, viable solid waste for anaerobic digestion come from urban and rural centres. Although seemingly a simple process, harvesting and/or collection has a significant environmental impact. The cultivation of biomass has a major contribution on the land and water footprint of the supply chain. Moreover, the energy used by collection facilities contributes to the carbon footprint.
- **Pre-processing** – Collected biomass may undergo pre-processing to increase its energy density. These pre-processing activities typically employed in BVCs include drying, baling and pelletizing to increase the energy density of biomass. Hence, the subsequent biomass conversion can be more efficient and sustainable. Moreover, densified biomass is more economical and environment-friendly for transport and storage. On the other hand, much of the carbon footprint of pre-processing is from the heat and/or electricity that power the facilities.
- **Storage** – Pre-processed biomass is either transported to conversion processes or stored for future demand. Essentially, temporal constraint in multi-feed BVCs becomes more

challenging as more types of feedstock are introduced. Normally, a storage facility is required to synchronise the biomass production calendar with the production plan of conversion processes. Hence, storage is a critical factor for BVCs. Storage facilities include simple stacks in plantation fields, in the farms, and in centralised storage sites. However, storage is not carbon-free, as this activity may require energy for cooling and other inputs required for biomass preservation. Storage technologies also allow BVCs to meet the changing product demand in the future.

- **Transportation** - Transportation technologies and infrastructures enable demand satisfaction of one or many resources through its movement from one geographic region from another region. In BVCs, pre-processed biomass is transported from pre-processing sites or storage sites to conversion plants. Converted biomass is then transported from the conversion plants to consumers. This can be done through several modes of transport such as road, rail, waterways or any combination of them. Among them, road transport is the most flexible but is typically used for short distances. Conversely, rail is preferred for medium to long distance transport. Lastly, water transport is the most suitable for long distance and in areas with close access to ports. In general, one or more transportation modes can be selected depending on the type of biomass, path shape and distance for distribution, and the demand of customers. Furthermore, the corresponding environmental impact of transportation is largely due to the greenhouse gas emissions when fossil fuel resources are used to power these facilities.
- **Conversion Processes**: The conversion processes generate the needed revenue for BVCs by transforming biomass resources (i.e. collected and/or pre-processed biomass) into valuable products. Among the typical technologies are gasification, pyrolysis, fermentation, gasification and anaerobic digestion. All of which allow low-value biomass resources to gain economic value when transformed into high-value products such as fuels, power, heat and oleochemicals [18]. However, the conversion efficiencies of these processes are limited by the stage of their technological development as well as the pre-processing done on the feedstock. The conversion efficiency plays an important role in the economic performance of a technology. Nevertheless, like the other activities in BVCs, conversion processes are not without their own environmental impacts. Depending on the process requirements, they have significant land, water and/or carbon footprint.

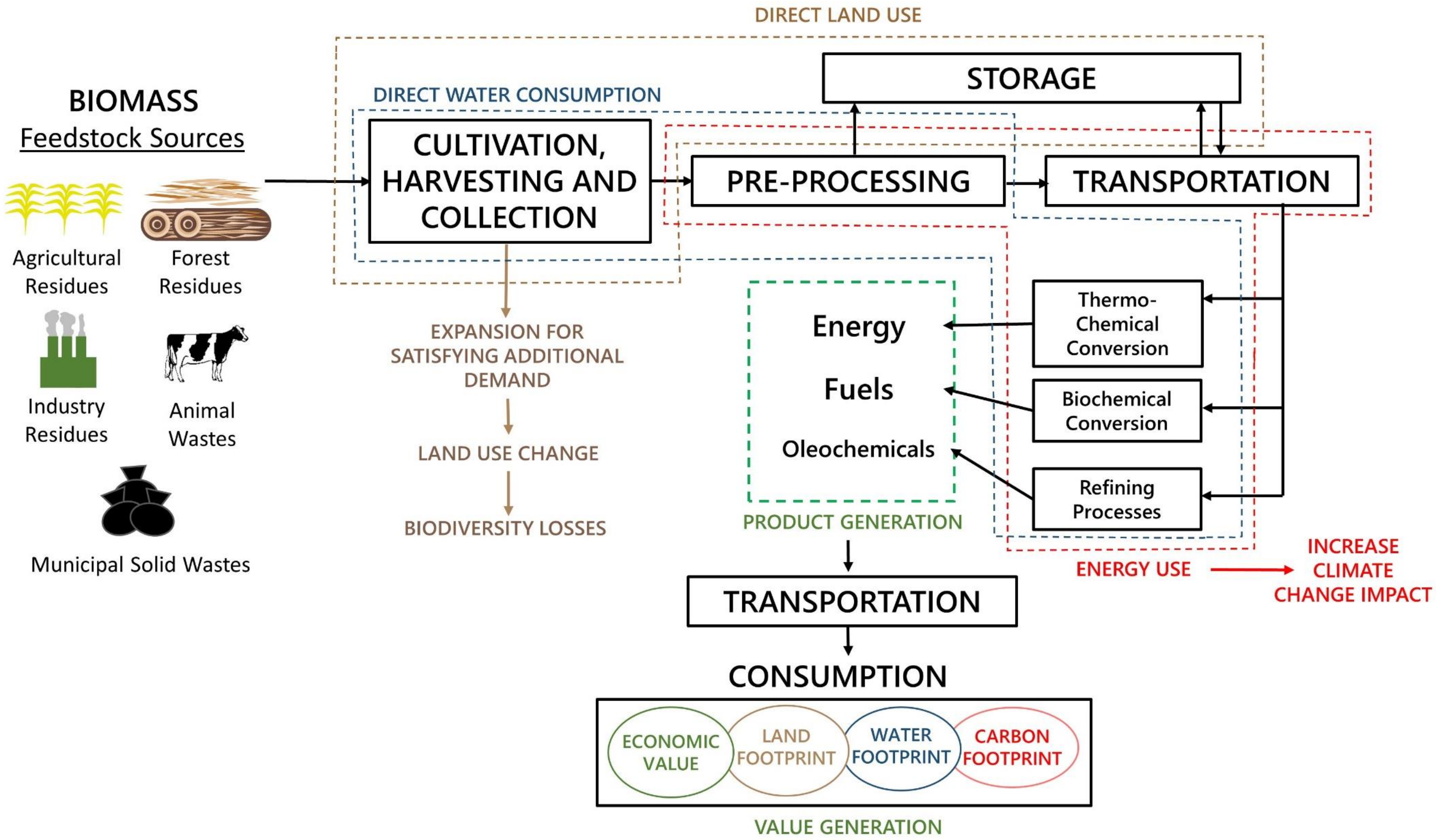

Figure 1: Typical activities in BVCs and some of the economic and environmental impacts.

The plan and design of BVCs must consider various factors such as biomass feedstock allocation, economic performance assessment and environmental impact assessment. On the allocation of biomass feedstock, this is notably influenced by the product demand, which varies accordingly though time and geographic locations. In terms of economic performance, the efficiency of conversion processes (whether integrated or not), as well as the transportation plans for distribution, significantly affect the profitability of BVCs. Finally, environmental impact assessment is essential in proving the sustainability of BVCs. From the discussion above and as shown in Figure 1, at least one impact is associated with each activity of the BVCs. Environmental impacts are also associated with value generation when the products reach the consumers. The direct implications of these impacts to the environment is also illustrated in Figure 1. Thus, in the next section, the sustainability of BVCs is explored in terms of its synergy with the FEW nexus. Then, the insights on the environmental impacts of BVCs on food, water and energy systems gained from mathematical programming tools are appraised in the succeeding sections.

SYNERGY OF BIOMASS VALUE CHAINS WITH THE FEW NEXUS

The idea of the FEW nexus was launched at the Bonn 2011 Nexus Conference. According to the background paper by Hoff in that conference, the concept of the FEW nexus emerged in the international community to address climate and social changes [19]. Conventionally, the study of one particular resource (e.g. water) and its subsequent impact on the environment is conducted in complete isolation from other resources (e.g. food and energy). The novelty of the FEW nexus concept comes from its system-thinking approach in analysing any resource. In this regard, Dalziell and McManus [20] stated, "*the emergent properties of a system cannot be understood by analysing the components of the system in isolation*". In addition, Newell et al. [21] stated, "*a system's performance cannot be optimized by optimizing the performance of its sub-systems taken in isolation from one another*". Thus, the FEW nexus approach aims to provide decision-makers with more meaningful insights on the three nexus areas for more effective policy and decision-making aimed at resource conservation. Consequently, the FEW nexus can provide insights to anticipate unforeseen consequences and seek common ground for different conflicting factors in BVCs [9]. In addition, this approach emphasises the explicit consideration, evaluation and optimisation of the three resources within a system boundary [22]. In this regard, the FEW nexus approach is important because it is in line with the aim of designing sustainable BVCs.

There are numerous advantages to the application of the FEW nexus approach in BVCs. These advantages include:

- *Encourages a systems-thinking approach* – allows a holistic resolution to be deployed on the area of study while ensuring that opportunities for wider integration of the FEW sub-systems exist.
- *An explicit measure of resource consumption* – emphasises identifying inter-linkages between the food, energy and water resources to measure resource consumption in a given BVC.
- *Exploring trade-offs* – stresses on optimising food, energy and water resource consumption, so that policy-makers can identify the pathways within the BVC that improves food, energy and water resource security.
- *Increasing system resilience* – focuses on identifying bottlenecks within a BVC and addresses the resulting vulnerabilities to increase overall resilience.
- *Bottom up approach* – enables capturing from the low system level details of biomass production, through the details of a processing facility, to the larger system level interactions between biomass and FEW supply infrastructures in a particular locality, region or country.

An example of a BVC, wherein the application of the FEW nexus approach can be beneficial, is in the production of first generation biofuels. These are mainly produced from food crops, which have shown the negative impacts of biomass utilisation such as increased food prices, land use changes, among others [9]. As a result, a more careful examination is needed on the sustainability of biofuels and other biomass-derived products, specifically their interactions with the food, energy and water systems along the value chains. First generation biofuels have been known to affect the food systems by diverting arable land from food production to energy production, the water system by introducing additional irrigation requirements in growing energy crops and production of wastewater in their processing, and the energy system by creating a new energy demand for processing but also possibly adding energy supply. Hence, a more systematic approach to planning biomass utilisation is required by considering a nexus approach wherein the interactions between the FEW nexus and BVC activities are carefully captured. The first step would be to identify such interactions in order to find their positive or negative impacts. A schematic of these interactions between the FEW nexus and BVCs is illustrated in Figure 2. These interactions can be of the following types:

- *Resource competition*. BVCs compete with the food, energy and water systems for input resources such as land, water or energy. This is the case of the so-called food versus fuel debate. Unless there is no constraint on the resource availability or the positive effects are much greater than the negative impacts, this kind of interaction should be avoided. When the priority to supply one or another product is not clear, an assessment of nexus resource allocation using indicators such as the resource gain can be useful [23].
- *Reinforcing or supportive*. The BVC contributes to achieving or enhancing the security of supply of food, energy or water in the nexus, or vice versa. For example, a new power plant using forestry residues can provide continuous energy access to remote localities. The large scale implementation of energy supply from solar irradiation could enable thermochemical or electrochemical processing of biomass into biofuels.
- *Synergistic*. The BVC and the FEW nexus support each other to balance resource trade-offs and obtain an enhanced overall performance. This is the kind of relationship that needs to be sought. For example, an anaerobic digestion plant processing food crop residues into energy and recovering nutrients for food crops, while treating wastewater is a kind of virtuous synergy that will enable sustainable value chains compatible with the constraints on the FEW nexus. Additional examples of synergistic interactions are shown in Figure 2.

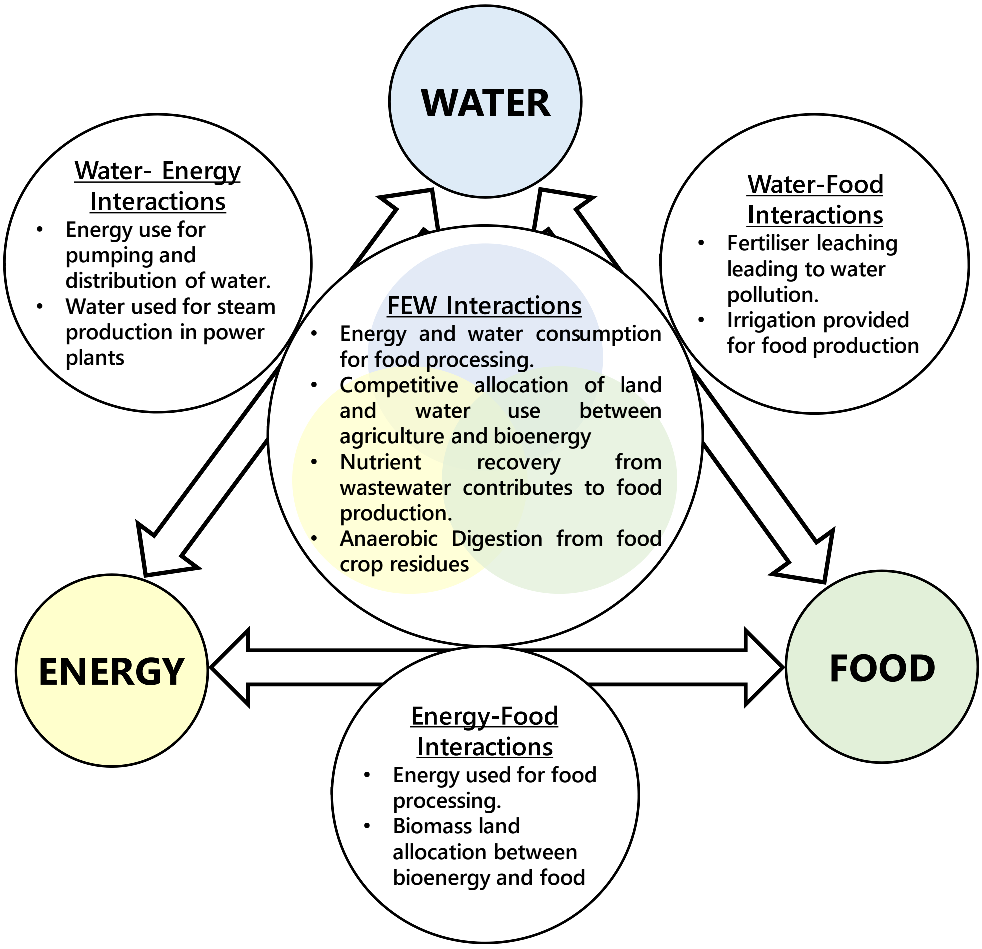

Figure 2: Example interactions between BVCs and the FEW nexus.

An interaction can be of one or two types and the kind of interaction dominant in a particular value chain will depend on where it is in the value chain (or at what stage) and the biomass feedstock. Furthermore, if the origin of the biomass is from an agricultural or a managed ecosystem, the system dynamics of the ecosystem need to be considered enabling timely supply of nutrients and water for biomass growth while maintaining or enhancing ecosystem states and services that support biomass availability and minimise environmental impacts [24]. In doing so, overshooting ecosystem capacity or depleting supporting resource stocks (e.g. water, nutrient or carbon in soil) and the wasting of resources is avoided; thus, enabling the long-term sustainability of the biomass supply.

Despite the advantages, the integration of FEW nexus considerations into BVC design remains a great challenge. In this respect, it is evident that there is a need for systematic approaches and process systems engineering (PSE) tools to support integrated decision-making [25,26]. Such tools allow decision makers to model the FEW nexus and explore scenarios based on scientific data to develop sustainable strategies for BVCs. This paper aims to discuss the contributions of PSE tools in fulfilling the following objectives:

- To determine the interdependencies between stages of the BVCs and develop an optimal BVC design and operation based on these interdependencies.
- To develop tools to capture the variations between different geographic regions and at different times in optimal planning of BVCs
- To capture the trade-offs between economic benefits and environmental impacts in planning and design of BVCs.
- To determine the effects of uncertainties in different factors in BVCs and manage the risks associated with them.

Mathematical tools are discussed based on these objectives and are justified as follows. Planning multi-stage BVCs account for the material and energy flows between stages, thus the interactions can be captured easily. The effects of spatio-temporal variations need to be captured to satisfy product demand at different times in different regions. Tools that simultaneously consider both environmental and economic objectives help in developing more sustainable BVCs. Lastly, managing risks associated with BVCs is important to successful interactions with the FEW nexus and to robust planning of BVCs. The following section provides a detailed review of the state-of-the-art models developed for designing and planning BVCs as well as evaluating FEW nexus considerations.

REVIEW OF MATHEMATICAL TOOLS FOR BIOMASS VALUE CHAINS

There are many models that have been developed for BVCs, which have been reviewed in a number of studies. Figure 3 shows a bibliometric progress of the area of process systems engineering (PSE) in biomass research for the past 30 years. There is an increasing interest in developing tools for biomass systems as shown in the increasing trend of contributions of PSE publications. Developments in BVCs have been reviewed several times, analysing progress in problem structure [27], mathematical approaches [28], and decision framework and application [12]. This review paper focuses on analysing the optimisation structure of each model and its contribution based on the FEW nexus. The models are classified according to stage-based, scale-based, objective-based and uncertainty-based approaches. Table 1 shows the general characteristics of each approach. A detailed review of these models is presented in the following sub-sections.

In general, BVC systems are complex, particularly when interactions with the FEW nexus are modelled. Having a single model to account for all of these interactions may require extensive computing power. Simplifications can be made depending on the constraints and system boundaries being considered. Furthermore, there are various PSE methods that can be applied to enhance the computational efficiency of complex systems such as BVCs, e.g. surrogate modelling and decomposition methods.

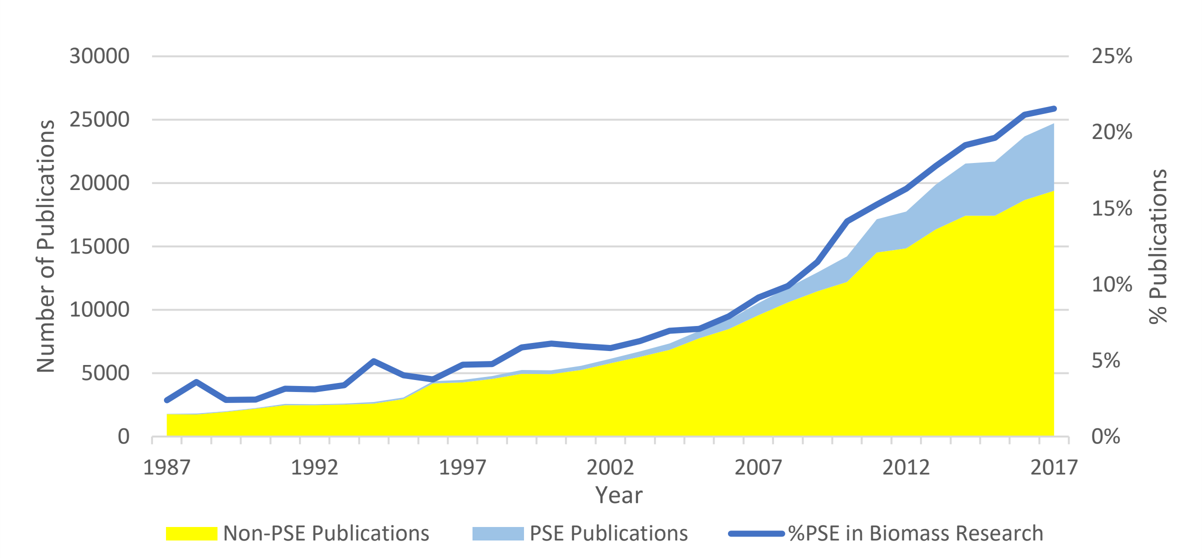

Figure 3: Overview of process system engineering (PSE) publications in biomass research.

Table 1: Process systems engineering approaches for BVC problems.

Approach	**Advantages**	**Disadvantages**
Multi-Stage Approach	Provides a more detailed approach in the material flows in the supply chain.	Increasing computational complexity with increasing number of stages.
Multi-Scale Approach	Captures the interaction between allocation, scheduling and transportation decisions.	Increasing computational complexity with higher spatial and temporal resolutions.
Multi-Objective Approach	Simultaneously consider the best solution for multiple factors such as environmental and economic objectives.	Subjectivity in determining which equally-optimal (Pareto) solution is to be used as basis for insights.
Uncertainty-Based Approach	Determines the effect of uncertainties on planning BVCs and gives insights to the user on how the risks associated can be managed.	Risk attitude, which depends on model user, requires expert knowledge.

Multi-stage approaches

Multi-stage models focus on modelling the interaction between different stages involved in a BVC. Models proposed consists of three-stage [29–31] or four-stage [32,33] supply chains. The complexity of solving multi-stage BVC models depends on the number of stages and their respective sizes (i.e. number of nodes). A multi-feedstock supply chain model was developed by Čuček et al. [32] considering carbon footprint from transportation and production stages. This model was later extended to a multi-period approach [33] to consider temporal variabilities (e.g. seasonality and availability of biomass, and purchase of raw materials). Lin et al. [29] developed a geographical information system (GIS)-based mixed-integer linear programming (MILP) model focusing on bioethanol production from Miscanthus biomass. The model was later extended to add more logistic factors such as farm equipment selection, transportation vehicles and biomass harvesting [30]. Pathway for corn stover fast pyrolysis was optimised in a MILP model developed by Zhang and Hu [31]. This model considers both single and multi-period approaches in the paper. However, these three papers [29–31] focus more on the economic side of the supply chain rather than on the environmental impact.

Numerous models have considered multi-stage supply chain for energy conversion of biomass. Such models include an MILP formulation for an energy supply chain of coal, biomass and natural gas to liquid (CBGTL) by Elia et al. [34]. It was used to develop a steady-state multi-echelon model for specific biofuels from forestry residues as the single biomass feedstock [35]. An MILP model for a three-stage rubber seed oil supply chain for biofuel production was developed by Ng et al. [36]. On the other hand, a P-graph approach was implemented by How et al. [37] to minimise computational difficulties in multi-stage biomass supply chain models. These two papers [36,37] used Malaysia's biomass resources to illustrate the methodology. These models emphasise energy and economic factors for optimisation of the biomass supply chain. The trade-off between environmental and economic factors was not emphasised in these studies.

A summary of mathematical formulation and environmental considerations made by these studies is shown in Table 2. The studies mentioned have made significant contribution on guiding policy-makers on the economics of BVCs via cost minimisation scenarios mostly. However, there have been only a few studies that considered the environmental impacts of BVCs such as their carbon, water and land footprint as well as a lack of emphasis of the synergies between the resources. It is important to note that the contributions mentioned in this section focus on multi-stage considerations for steady-state scenarios. Due to varying availability of biomass supply and energy demands, it is imperative that design approaches for BVCs should consider multi-scale elements such as spatial and temporal representations. The following section reviews contributions on multi-scale approaches for BVCs.

Multi-scale approaches

BVC modelling has been applied to various scales, otherwise known as multi-scale approaches. In multi-scale approaches, models include spatial scales, temporal scales or a combination of both. Spatial scales refer to the use of data relating to land use, land cover and spatial availability in a defined region or country. Meanwhile, temporal scales include both short-term (months, years) and long-term (decades) dimensions [38]. Considering long- and short-term time horizons in planning can lead to insights about the magnitude of the cascading effects in supply chains [9]. In current literature, multi-scale considerations have gained substantial attention in BVC modelling. For instance, Dunnett et al. [39] adapted a model previously developed by Almansoori and Shah [40] for a biomass-to-ethanol supply chain. In this model, full spatial representations are utilised with the aid of echelons (stages) to investigate the trade-offs between centralised and decentralised pre-processing of biomass. GIS has been a useful tool for extracting relevant insights from the spatial planning of BVCs including their feasibility of delivery within networks [41], comparison of biomass supply chain data [42] and minimum-cost delivery networks [43]. A biomass supply chain model was developed by Giarola et al [44] which considers first and second generation biorefineries in Northern Italy. This model contained a more detailed finance formulation as compared to works published by Dunnett et al. [39] and Almansoori and Shah [40]. The contribution of Marvin et al. [45] in their MILP biomass supply chain model is the consideration of governmental policies with elaborate financial details on biomass supply chain facilities.

Putting spatial and temporal scales in mathematical programming models is computationally challenging under environmental constraints. This problem was addressed in Biomass Value Chain Model (BVCM) by Samsatli et al. [46] which provides a comprehensive and flexible toolkit for large-scale biomass supply chain illustrated for United Kingdom (UK) biomass scenarios. Decision factors considered include CO_2 sequestration potential, conversion technologies, land allocation for many different biomass types (arable, energy crops, and forestry), crop yield scenarios, transportation and storage, and sale and disposal of resources.

A new formulation was later developed for hybrid energy supply chains considering energy carriers such as hydrogen, syngas, electricity from wind power, natural gas and biomass [47]. This model captures intermittency and dynamic behaviours in energy storage [48]. Detailed mathematical formulations of storage for properties such as charging, maintaining and discharging inventory were presented [49], as well as detailed modelling of transport of resources across the country [50]. The objectives considered were maximising profit and renewable energy production, minimising cost and emissions taking into account temporal variations and spatial distributions. Samsatli and Samsatli [51] also presented a detailed spatio-temporal multi-objective MILP model that can simultaneously optimise the design and operation of integrated heat and electricity networks for eco-towns supplied by different types of biomass and by the national electricity and natural gas grids as back-ups when there is a shortfall in energy generation. Conversion technologies involved in the network include domestic chip boiler, natural gas boiler, and combined heat and power (CHP) technologies.

Some spatial-based planning frameworks also integrate GIS data, simulation and optimisation methods. Zhang et al. [52] proposed an integrated methodology that selects biofuel facility locations in the USA for simulation and optimisation of biofuel production. Likewise, Ng and Maravelias [53] proposed a discrete-time multi-period MILP model for the design and operational planning of cellulosic biofuel supply chains in the USA. Decision factors such as biomass selection and allocation, technology selection and capacity planning at regional depots and biorefineries are considered. A summary of multi-scale models is presented in Table 3.

Based on the multi-stage and multi-scale contributions, it is found that single objective optimisation was given a large focus. Only a few papers considered multiple objectives for planning. However, designing real-world applications would often consider conflicting objectives such as economic, environmental and social aspects. For policy-making, mathematical tools would need to give insights on how these objectives interact. Single objective problems may then lead to undesired preferences for other objectives. To address this issue, multi-objective approaches have been developed. The application of multi-objective approaches in the design of BVC's is discussed in the following section.

Multi-objective approaches

Multi-objective approaches are used to optimise a value chain according to two or more conflicting objectives, simultaneously. In BVC's, targets for multiple conflicting factors such as economic and environmental factors are often difficult to set, thus, multiple objectives are generated. Multi-objective approaches become available to provide insights about the interaction between these objectives. For instance, Čuček et al. [54] presented a multi-objective optimisation model for regional biomass supply chains. Economic performance, environmental and social footprints were considered. Results from this model suggested that biomass energy required more water, transportation and chemical input than fossil energy. A multi-period, multi-objective approach for planning biofuels production was develop by Santibañez-Aguilar et al. [55] focusing on economic, environmental and social impacts. Zore et al. [56] developed an index based on a multi-criteria evaluation of a sustainable supply network. This involves representing environmental impacts in monetary terms required for unburdening the environment or for avoidance of negative environmental impact. It also represents the social impact with monetary value equal to social security contributions. The model aggregates these impacts into sustainability profits. A summary of multi-objective models is presented in Table 4.

Despite the usefulness of the multi-objective approaches, they have generally been applied only to deterministic problems, i.e. where it is assumed that all of the inputs to the model, such as demands, costs, efficiencies, are known precisely. Generally, the purpose of multi-objective optimisation models for BVCs is to provide the interactions between different socio-economic and environmental factors. The insights obtained from this model enable policy-makers to choose between different possible alternatives for planning but it will depend on how much weight is put on each factor. On the other hand, models considering uncertainties in BVCs, such as prices, demand and seasonality, are powerful tools in providing robust and flexible planning frameworks. The next section will discuss uncertainty-based optimisation for planning and designing BVC models.

Uncertainty-based approaches

Uncertainty is an important factor which can significantly influence the performance of BVCs [57]. Biomass feedstock supply, biofuel demand, bioenergy production, price, logistics, and transportation are all common sources of uncertainty in BVCs [58]. Decision approaches suggested in the literature allows model users to manage risks due to uncertainties by dividing the planning horizon into more than one decision stages [59]. Such models include stochastic MILP model for planning multi-echelon biofuel supply chains under market uncertainty [60].

Biomass and carbon market uncertainties [61] and climatic condition uncertainties [62] were considered. Different strategies were also employed for model development for BVCs with uncertainties. Giarola et al. [63] considered market uncertainties in a risk-constrained multi-objective stochastic MILP model in order to determine the strategic planning decisions and design of a bioethanol supply chain. Strategic planning and feedstock allocation decisions were also emphasised by Chen and Fan [64] in their mixed integer stochastic programming model. A systematic method for planning of biomass distribution network was developed to design a robust value chain under different market demand scenarios [65]. On the other hand, a stochastic mixed integer program (MIP) was developed based on the risk attitude of the decision-makers under different economic and environmental scenarios [66]. These studies [65,66] considered decision factors regarding biomass transportation such as facilities location and amount of biomass for transportation. Other strategies that were used in different models focused on risk management based on the uncertainties identified. A dynamic, stochastic MILP managing market risks was developed by Azadeh et al. [67] in order to manage market risks in biomass supply chains. Whereas, Gebreslassie et al. [68] developed a multi-period stochastic MILP to manage simultaneously annual costs and financial risks. Likewise, Tong et al [69] studied the design and planning of the hydrocarbon biofuel supply chains. Foo et al. [70] presented a robust linear programming (LP) model to synthesise biomass allocation networks that exhibit operational flexibility under multiple biomass supply scenarios such as closure or expansion of palm oil mills. Demand uncertainty was highlighted by Kostin et al. [71] for their stochastic MILP of sugar and ethanol supply chain. Multiple uncertainties were considered by Tong et al. [72] in their proposed a stochastic MILP model. These uncertainties include biomass availability, biofuel price, crude oil demand, and production technology. Advanced biofuel supply chains minimise the biomass transportation costs, and they have the advantage of economies of scale for the bio-oil gasification facilities. In this regard, Li and Hu [73] proposed a two-stage stochastic MILP based on bio-oil gasification in which factors such as biomass availability, technology advancement, and biofuel price were assumed as uncertain parameters. More recently, Gong et al. [74] proposed a two-stage adaptive robust mixed-integer nonlinear programming (MINLP) model. The MINLP model allows for decisions at the design and operational stages to be made sequentially (i.e. investment at the first stage and operation at the second stage) and considers budgets of uncertainty to govern the level of robustness. Samsatli et al. [46] managed uncertainty by providing a stochastic analysis within the BVCM, which accounts for the uncertainties in biomass yields and costs, technology costs and efficiencies. A summary of uncertainty-based models is presented in Table 5.

Table 2: Multi-stage models for BVCs.

Model	Environmental impact considered	Objective(s)	Number of supply chain stages	Model type
Čuček et al. [32]	Carbon and land footprint	Profit maximisation	4	MILP
Čuček et al. [33]	Water, land and carbon footprint	Profit maximisation	4	MINLP linearised by piecewise linear approximation
Lin et al. [29]	n/a	Cost minimisation	3	GIS-based MILP
Lin et al. [30]	n/a	Cost minimisation	3	GIS-based MILP
Zhang and Hu [31]	n/a	Cost minimisation	3	MINLP linearised by ancillary variables
Elia et al. [34]	n/a	Cost minimisation	2	MILP
Elia et al. [35]	n/a	Cost minimisation	2	MILP
Ng et al. [36]	n/a	Cost minimisation	3	MILP
How et al. [37]	n/a	Profit maximisation	3	P-graph based MILP

Table 3: Multi-scale models for BVCs.

Model	**Environmental impact considered**	**Objective(s)**	**Modelling scale considered**	**Model type**
Dunnett et al. [39]	n/a	Cost minimisation	Spatial	MILP
Almasoori & Shah [40]	n/a	Cost minimisation	Spatial	MILP
Perpiñá et al. [41]	n/a	n/a	Spatial	GIS
Yazan et al. [42]	Carbon footprint	n/a	Spatial	GIS
Frombo et al. [43]	Biodiversity loss	Profit maximisation	Spatial	GIS
Giarola et al. [44]	Carbon and land footprints	Multiple	Spatio-temporal	Multi-objective MILP
Marvin et a. [45]	n/a	Profit maximisation	Spatial	MILP
Samsatli et al. [46]	GHG and non-GHG emissions and land footprints	Multiple	Spatio-temporal	Multi-objective MILP
Samsatli & Samsatli [47]	Carbon and land footprints	Multiple	Spatio-temporal	Multi-objective MILP
Samsatli & Samsatli [48]	Carbon footprint	Multiple	Spatio-temporal	Multi-objective MILP
Samsatli & Samsatli [49]	Carbon footprint	Multiple	Spatio-temporal	Multi-objective MILP
Samsatli & Samsatli [50]	Land footprint	Cost minimisation	Spatio-temporal	MILP
Zhang et al [52]	Carbon footprint	Cost minimisation	Spatial	MILP
Ng & Maravelias [53]	n/a	Cost minimisation	Spatial	MILP

Table 4: Multi-objective models for BVCs.

Model	Environmental impact considered	Objective(s)	Highlights	Model type
Čuček et al. [54]	Energy, water, agricultural, and water pollution footprint	Economic and Environmental	- Indirect and direct environmental footprints are considered. - Four supply chain stages are considered for the modelling framework.	Multi-objective MILP
Santibanez-Aguilar et al. [55]	Damages to ecosystem, resource extraction, and human health	Economic and Environmental	- Multiple environmental impacts are considered for each stage - Multi-period approach is used to consider seasonal variations in biomass yield.	Multi-objective MILP
Giarola et al. [44]	Carbon footprint	Economic and Environmental	- The model considered resource production and transportation in a multi-regional and multi-period setting. - Trade-off between economic and environmental performance is analysed	Multi-objective MILP
Samsatli et al. [46]	Land footprint, waste utilisation, greenhouse gas emissions	Economic and Environmental	- A comprehensive biomass planning model is developed. - Multiple biomass feedstock are considered in the modelling framework.	Multi-objective MILP
Zore et al. [56]	Environmental damage as economic cost	Economic, Social and Environmental	- Multiple objectives are aggregated using an indicator called Sustainability Profit (SP)	Multi-objective MILP
Samsatli & Samsatli [47]	Carbon and land footprints	Economic and Environmental	- Investment and retirement of production, transportation and storage technologies are included in the model. - Multiple environmental and economic objectives are aggregated using weighted sum.	Multi-objective MILP

Table 5: Uncertainty-based models for BVCs.

Model	**Environmental Impact Considered**	**Objective(s)**	**Uncertain parameters considered**	**Model type**
Dal-Mas et al. [60]	Land footprint	Profit maximisation	Market	Multi-echelon MILP
Giarola et al. [61]	GHG impact	Profit maximisation	Biomass and carbon market	Multi-period MILP
Sharma et al. [62]	Land footprint	Cost minimisation	Climatic	MILP
Giarola et al. [63]	GHG impact	Multiple	Market	MILP
Chen & Fan [64]	n/a	Cost minimisation	Supply and demand	Two-Stage SP
Kim et al. [65]	n/a	Profit maximisation	Demand	MILP
Walther et al. [66]	n/a	Profit maximisation	Financial (scenario-based)	Multi-period MILP
Azadeh et al. [67]	n/a	Profit maximisation	Market	Linear SP
Gebreslassie et al. [68]	n/a	Cost minimisation	Financial risk	Multi-stage SP
Tong et al. [69]	n/a	Cost minimisation	Multiple	MILP
Foo et al. [70]	Carbon footprint	Carbon footprint	Scenario-based	MILP
Kostin et al. [71]	n/a	Profit maximisation	Demand	Two-Stage SP
Tong et al. [72]	n/a	Cost minimisation	Financial (scenario-based)	SP
Li & Hu [73]	Land footprint	Profit maximisation	Multiple	Two-stage SP
Gong et al. [74]	n/a	Cost minimisation	Biomass price and product Demand	Deterministic and robust MINLP
Samsatli et al.[46]	GHG and non-GHG emissions and land footprints	Multiple	Biomass yields and costs, technology costs and efficiencies	Deterministic and stochastic MILP

SP= Stochastic Program, MILP= Mixed integer linear program, MINLP= Mixed integer nonlinear program

Analyses of the current progress of BVC models

Based on the approaches made by different studies, it is evident that uncertainty-based approaches have been given some focus in BVC modelling. Uncertainties especially in the economic side of the value chain, affect temporal decisions on investment and allocation of resources [58]. The approaches presented allow the management of uncertainties subject to policy-makers' aversion to risk. While uncertainty-based models are mostly stochastic in nature (60% based on the publications reviewed), a few papers [59,70,73,74] have presented robust planning models for BVCs. Such models reduce user's subjectivity when it comes to risk by setting a fixed decision variable that can handle the full range of uncertainty and a flexible decision variable that may be adjusted when the uncertainty is realised. For instance, Foo et al. [70] developed a robust optimisation model in which for all scenarios, the link between empty fruit bunch (EFB) source and demand is fixed and the amount of EFB allocated is flexible in different scenarios. Other approaches such as multi-scale, multi-objective and multi-stage models provide powerful tools for decision making in BVC planning. Multi-scale approaches determine the interaction between spatial and temporal scales in BVC planning. On the other hand, multi-objective models give multiple equally optimal solutions in which the user can gain insights on the effect of one objective on another. Some models can be classified into more than one type. For instance, Samsatli et al. [46] developed a comprehensive BVCM for biomass supply chain considering temporal and spatial scales, multiple user-defined objectives and multiple supply chain stages, with options for stochastic uncertainty analyses. Although including these factors simultaneously approaches the realistic BVC structure, the computational complexity is also significant. The computational complexity of the model exponentially increases as the number of stages increases and the number of sources, processes or sinks increases in each stage.

A summary of the bibliometric analysis of the studies reviewed in this paper is presented in Figure 4, which shows the cumulative number of publications for each category. The increase in the use of spatial approaches to BVC modelling could be due to the advancement of Geographical Information Systems (GIS) tools and other tools that can be used to manage and process spatial data. In particular, the availability and accessibility of spatial data (e.g. biomass resource availability, land cover, and land use) from governmental/non-governmental databases, have increased over the years. Meanwhile, spatio-temporal considerations have only recently gained attention. This could be due to an increased need to perform periodic long-term planning horizon for BVC's. This provides decision-makers with more accurate spatial and temporal representations for BVC models to conduct bioenergy market forecasts. It is noted that multi-objective approaches have received very limited attention between 2008 and 2017. In the authors' opinion, such limited attention could be due to the emphasis on optimising the economic objectives of the BVC's. In particular, if the BVCs are not economically favourable, stakeholders would not be convinced of their feasibility and thus would not be concerned about other objectives such as environmental and social aspects.

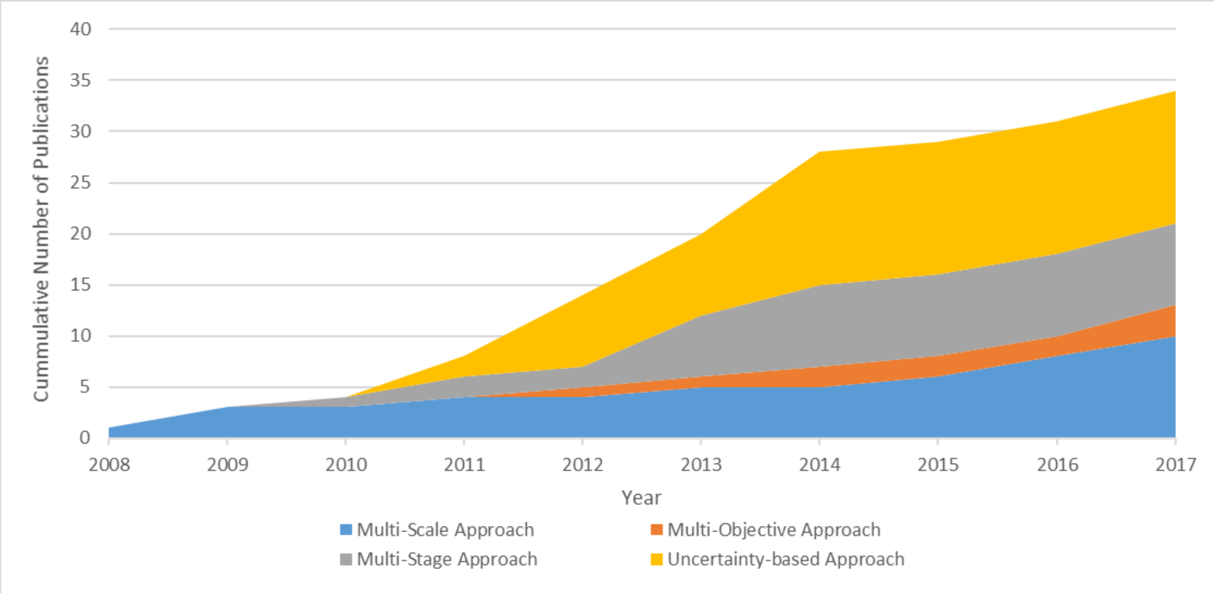

Figure 4: Bibliometric summary of the various approaches for BVC design.

Overall, the literature available on BVC models provides different options for tools on decision-making and policy development for biomass and bioenergy. While most of the models presented in the literature focus on the economic aspect of BVCs, some studies examine in their model the environmental impacts of BVCs. Table 6 shows a summary of the environmental aspects considered in the studies where it is reviewed. Land and CO_2 footprints were considered in these studies due to the effect of land use competing with agriculture and energy production and consumption in the BVC, respectively. On the other hand, the water footprint was also considered but with less emphasis in different studies. A more detailed approach to estimate the environmental impact of a BVC design is needed.

Table 6: Environmental aspects as a factor to considering in developing BVC models.

Environmental aspect	How it is addressed in previous studies
Water footprint	• Considered in the objective function for multi-objective approach [54] • Water consumption is accounted for each collection, preprocessing and storage facility, and biorefinery in the modelling framework [33]
Land use	• Expressed as a constraint in the modelling framework [33] • Classified into different environmental impacts related to land use [55] • Expressed as a constraint based on suitability [44] • Expressed as availability for energy use [50]; as resource constraints [51]; and for land allocation and land use change constraints [46].
Carbon footprint	• Used for measurement for considering carbon trading scheme in bioethanol supply chain [61] • Used as an objective function in developing robust mathematical programming for EFB allocation in palm oil value chain [70]
GHG and non-GHG emissions footprint	• Used as a key performance measure for each of the activities involved in the BVC and as an objective function in a spatio-temporal, multi-objective, multi-feedstock and multi-product BVC model [46]
Biodiversity loss	• Indicated as a constraint on forest biomass collection. [43].
Multiple	• Classified between indirect and direct footprints [54] • Classified between different negative impacts to human health, ecosystem and resource extraction [55] • Converted into equivalent economic damages [56]

From this review, it is noted that the interaction between food, energy and water system are given less priority when it comes to model development. These interactions are strong in case of biomass systems especially biorefineries [15] and supply chain [9]. Biomass systems pose significant impacts on land use, energy production and water consumption. In BVCs, noticeable impacts such as competing land use for agriculture, energy use associated with fertiliser production and water consumption on irrigation is evident in feedstock cultivation. Biomass processing also requires energy for conversion as well as transportation for product distribution. These impacts should be taken into account when planning and designing BVCs, such that their impacts on the FEW nexus are simultaneously considered as well as the interdependent nature of the BVCs and the nexus is captured. From this review and analysis, it can be concluded that there is limited work on BVC models that integrate FEW nexus approach. However, with the increasing interdependencies between the food, energy, and water systems, the necessity for a nexus approach is becoming crucial to enable sustainable development and mitigate the adverse impacts of climate change. The following section reviews the models for the FEW nexus.

REVIEW ON THE FOOD-ENERGY-WATER NEXUS MODELS

Recent literature has emphasised the importance of modelling the FEW nexus. For instance, Bazilian et al. [75] emphasised the importance of systems-thinking in addressing interdependencies of resources in the nexus in policy-making. Specifically, this work provided a rationale for addressing the nexus in a quantitative manner and presented a modelling framework to support effective policy and regulatory design. Aside from this, linkages of the nexus were described at a high-level of aggregation via case studies (of developing countries) to formulate directions for addressing the FEW nexus. Al-Saidi and Elagib [76] reviewed the key drivers for the FEW nexus towards an integrative approach. In this review, key drivers identified include the increasing resource interlinks due to growing scarcities, the recent resource supply crises, and the failures of sector-driven management strategies. Moreover, Al-Saidi and Elagib [76] pointed out that there is no uniform way to integrate the FEW nexus. Similarly, Endo et al. [77] presented a review based on regions studied, nexus keywords and relevant stakeholders. Based on their review, contrastingly, they emphasised the need to develop a unifying framework of the nexus to understand the complexities of FEW systems in order to reduce trade-offs and increase synergies between these three systems. In this regard, the nexus simulation system (NexSym) allows the dynamic modelling and analysis of locally integrated production systems with food, energy, water and ecosystem nexus interactions [78].

Process systems engineering (PSE) offers opportunities for developing unified frameworks to address the FEW nexus. Garcia and You [26] identified PSE research opportunities to model and optimise the FEW nexus. These opportunities include the consideration of multiple spatial and temporal scales, multi-scale uncertainty, life cycle optimisation and multiple stakeholders and objectives. Likewise, Shastri [79] reviewed recent developments in ligno-cellulosic and micro-algal biofuels from a chemical engineering perspective. The review pointed out the FEW nexus would be at the centre of the sustainability debate in the coming years and that integrated system tools are required to capture dynamics and sectoral interdependencies. Meanwhile, Martinez-Hernandez and Samsatli [15] presented a review on how biorefineries can be a potential solution to the FEW nexus issues. In this review, the importance of developing process integration and optimisation methods for synergistic interactions with the nexus components was highlighted. Furthermore, they discussed opportunities for PSE tools at the process level and at the entire BVC for efficient utilisation of FEW resources. The opportunities identified at the process level are in the food element of FEW nexus and the focus on processing of residues and wastewater for nutrients in food cultivation. On the other hand, opportunities identified at the value chain level are the linking of different stages of a biomass supply chain with the nexus in a complex manner.

Based on the emphasis placed by the contributions above, it is important to note that several publications have considered the FEW nexus in the modelling framework for resource management. For instance, Leung Pah Hang et al. [80] developed a model for designing local production systems where they defined the FEW nexus system as a system that takes advantage of opportunities for synergy and integration arising from closely and geographically co-located subsystems for food, energy and water production. In addition, this work adopted a life cycle accounting approach using exergy analysis and studied building blocks of food, energy and water production subsystems, respectively. Meanwhile, Zhang and Vesselinov [81] developed a bi-level decision model, which improves upon the existing studies by integration of bi-level programming into energy-water nexus management. The developed model uses an interactive fuzzy optimisation methodology to seek a satisfactory solution to meet the overall satisfaction of the two-level decision makers. The trade-offs between the two-level decision makers in energy-water nexus management are effectively addressed and quantified. The proposed model used a representative example problem to show its applicability in practical energy-water nexus management. Next, Zhang and Vesselinov [82] presented a FEW integrated multi-period analysis framework. The proposed framework is capable of identifying trade-offs among the food, energy and water resources. Similar to Zhang and Vesselinov [81], the framework was applied to a hypothetical FEW management problem. The framework analysed interrelationships and trade-offs among system components including energy supply, electricity generation, water supply-demand, food production as well as mitigation of environmental impacts. Global sensitivity analysis was performed on the model parameters to evaluate the impact of uncertainties in these parameters on the total system cost. Lastly, the nexus performance was measured based on a composite objective function that consists of cost for energy supply for electricity generation, water supply, food production and CO_2 emission abatement. However, it is important to note that these contributions are focused on developing FEW nexus approaches and do not consider its application for value chains. Recent developments on developing FEW nexus frameworks include synthesis matrix for simultaneous qualitative and quantitative assessment of the nexus [83], regional energy planning considering nexus interactions [84] and design of sustainable food-water-energy system [85]. Nie et al [86] developed a land allocation framework that can generate a FEW index to integrate the nexus components. A life cycle-based framework was developed by Yuan et al. [87] using spatial optimisation approaches to assess bioenergy feasibility in a given region. These works have considered interactions between systems in the FEW nexus using life cycle analysis [83] and optimisation approaches [84–86].

In the area of value chains, Gao and You [88] developed a mixed-integer linear fractional programming (MILFP) model to determine the optimal design and operation of water supply chain networks in shale gas production. A fractional programming approach involves simultaneous minimisation of freshwater consumption and maximisation of profit. The objective set for this model is to maximise profit per unit freshwater consumption, such that both economic performance and water-use efficiency are optimised. Input-output (IO) analysis was used for ranking economic sectors based on its impact on the energy, water, and food systems [89]. White et al. [90] proposed an inter-regional IO analysis for value chains based on the FEW nexus, which demonstrates the hidden virtual flows of water, energy, and food in inter-regional trade. IO analysis captures the interdependencies of economic sectors and takes into account the flows of different commodities such as energy, food and water between them.

Despite the usefulness of these contributions, it is evident that the FEW nexus has not been explicitly addressed for BVCs. To date, limited work is found in this area. For instance, López-Díaz et al. [91] proposed a MILP optimisation framework for the design of a biorefining system while accounting for the interactions with the surrounding watershed. This work is performed using a material flow analysis technique to design an efficient supply chain for the production and distribution of feedstock, grains and biofuels considering the water and land requirements.

FUTURE DIRECTIONS

In light of the aforementioned review and analyses, a number of future research directions in BVC modelling are identified:

FEW nexus in BVC modelling

The integration of the FEW nexus with the design of BVC's requires more focus in the near future. The objective is to investigate how food, energy, and water resources are quantitatively interlinked in various stages of the BVC. A key part of the proposed quantitative analysis is to define measurable nexus metrics, for which data on both supply and demand sides are needed, as well as for the life cycle of each resource input or product. The results of this direction would contribute to solving the complex challenges of the FEW nexus by: (1) identifying characteristics (e.g. deterministic or stochastic) and processes to design FEW nexus approach in models of BVCs; (2) exploring and quantifying the driving factors (e.g. climate conditions, policies, energy markets) on the FEW nexus in BVCs; and (3) estimating the water and energy intensity of energy and food production for different types of BVC. Finally, the model should be able to express the interactions between food, water and energy systems in the nexus because it will be helpful to estimate the impacts on other systems when certain policies are proposed to one system in isolation to the other systems.

Utilising spatio-temporal data

Spatial and temporal data enable decision-makers to investigate where, when and how long changes in the FEW nexus occur in BVCs. The appropriate resolution of the spatial and temporal data should be carefully selected to balance the trade-off between complexity and accuracy. Through data on spatial scales, the geographic region's condition (e.g. land cover type, rainfall data, temperature range, and terrain condition) can be assessed and the portion of the land that can be developed in a given region in relation to the BVC can be determined. The spaces affected can range from localised areas and specific locations to large and far-spread regions. Spatial data that can be useful for BVCs include locations of water supplies and biomass plantations, and land availability. With such data, decision-makers are able to determine the means of transporting products and/or intermediates, determine the availability of food, energy and water resources in a given BVC, and effectively plan the locations of new facilities. Meanwhile, data on temporal scales can include hourly (e.g. solar and wind power output), daily (e.g. resource consumption), monthly/seasonal (e.g. biomass yield), and yearly/decadal (e.g. investments in technologies, land use change effects) variations. On the other hand, temporal data such as temporal energy and product demand as well as the seasonal production of biomass can prove useful in managing and optimising the operations of BVCs. Overall, by assessing both spatial and temporal scales simultaneously in a model, it permits understanding on causes and contributors to changes in the FEW nexus for BVCs. Based on these, the impacts of decisions in a given BVC on the FEW nexus can be quantified and analysed.

Improvements on multi-scale approaches

A multi-scale approach is desirable in regional planning of BVCs. It enables generation of insights based on the interaction of spatial and temporal factors in the value chain. Recent developments on multi-scale approaches focus on the economics of the value chain. This calls for an effort to develop tools that allows decision-makers to get insights not only on how economically feasible BVC networks are but also how several sustainability factors interact. Such strategy should incorporate FEW nexus thinking into the approach and enable better environmental policies.

The FEW nexus manifests in unique ways in different localities while global conditions may affect each location differently. Therefore, there is a need for approaches that can capture the important effects at the local scale so that solutions are better tailored to local conditions and to make it easier to target synergistic interactions. However, the approach must be sufficiently flexible to adapt the level of the study to a scale relevant for policy making. In particular, approaches which are able to model how local and regional decisions affect national development, and vice versa, are required.

Improvements on multi-objective approaches

In BVCs, the FEW nexus presents a complex multi-objective problem. For instance, it is imperative that BVCs produce large amounts of food and energy. However, this often occurs at the expense of high water consumption. This contradicts the goal of minimising energy and water intensity across the value chain. Due to such conflicts, it is challenging to reach a win-win scenario across the FEW nexus in BVCs. In this sense, multi-objective optimisation approaches are useful tools to compare and facilitate trade-off analysis for the FEW nexus in BVCs. It can be used to minimise energy and water intensity of a BVC along with maximising energy and food production rates. By doing this, several FEW nexus trade-off solutions can be generated for the BVC. These solutions are essential to provide decision-makers insights on several potential trade-offs prior to implementing a BVC design.

Improvements on uncertainty management approaches

The uncertainty associated with food, water and energy resources makes FEW nexus modelling in BVCs more complex. For instance, weather fluctuations and climate change influence the performance of the food, energy and water systems in the BVC. Furthermore, technological advancement is also uncertain as future population and the corresponding food, energy and water consumption levels both increase with time. Collectively, such uncertainties require the use of stochastic and/or robust modelling for future scenario analysis. Such modelling approaches must represent the close linkages and interactions across the FEW nexus, while also being dynamically capable of representing future challenges raised by population growth, climate change, resource depletion, technology change, and infrastructure depreciation along with other forces. In this respect, information is needed on many different items, including: (1) regional impacts on the economy; (2) food, energy, and water demand and supply, and associated price levels; (3) alternative ways of producing FEW nexus-related products; and (4) allocation of land and water.

CONCLUSIONS

This work surveyed and analysed the models for planning and designing biomass value chains (BVCs) in synergy with the food-energy-water (FEW) nexus. A significant number of studies present models for multi-stage, multi-scale, multi-objective and uncertainty-based planning of BVCs. Some of the key insights from this review are the following:

1. The representation of the BVC as a multi-stage supply chain model provides more detailed insight on resource allocation at the expense of computational power.
2. Spatio-temporal data are required for multi-scale BVC models.
3. Limited attention is given to framing multi-objective approaches in the context of FEW nexus. The approach can be used for integrating the sectors in FEW nexus frameworks in BVC models.
4. It is crucial to consider uncertainties in BVC models, especially in key factors such as biomass and biofuel/bioenergy market prices, biomass yields, technological costs and availability, governmental policies and subsidies among others.

New models for BVCs must successfully integrate different economic factors such as product demand, capital costs, transportation costs, storage costs and commodity prices. There are significant approaches presented that consider environmental factors such as land, water and carbon footprint for modelling BVCs. However, there is a lack of mathematical framework that utilises the concept of the FEW nexus in modelling BVCs. The interactions between different environmental aspects such as land use, greenhouse gas emissions and water consumption are important in BVCs, as activities in BVCs are closely associated with any of these aspects. Future directions of this field need to be focused on the balance between sustainability factors (i.e. economic, environmental and social factors).

In exploring opportunities for synergistic interactions between BVCs and the FEW nexus, a whole systems approach would support the development of resilient BVCs. If such an approach is timely applied during design and planning stages, biomass will not only allow balancing FEW nexus trade-offs, but deliver its promising potential for the sustainable development of our society.

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