MULTI-CRITERIA ANALYSIS OF AGRICULTURAL BIOENERGY CHAINS

Srđan VASKOVIĆ*,[1] Milica PERIĆ [2], Petar GVERO [3], Mirko KOMATINA[4], Milan JUGOVIĆ[5]

[*1]Faculty of Mechanical Engineering, University of East Sarajevo [1], 30 Vuka Karadžića Street, 71123 East New Sarajevo, Republic of Srpska, BiH

Innovation Center, Faculty of Mechanical Engineering, University of Belgrade, [2]16 Kraljice Marije Street, 11120 Beograd 35, Serbia

Faculty of Mechanical Engineering, University of Banja Luka[3], 71 Vojvode Stepe Stepanovića Street, 78000 Banja Luka, Republika Srpska, BiH

Faculty of Mechanical Engineering, University of Belgrade[4], 16 Kraljice Marije Street, 11120 Beograd 35, Serbia

Faculty of Agriculture, University of East Sarajevo[5], 30 Vuka Karadžića Street, 71123 East New Sarajevo, Republic of Srpska, BiH

[*]Corresponding author; srdjan.vaskovic@ues.rs.ba

This study proposes optimal supply chain models for agricultural biomass, focusing on straw and corn stalks. Four bioenergy chains—corn stalk pellets, corn stalk chips, straw bales, and straw pellets—were evaluated using multicriteria decision-making (MCDM) tools and life cycle assessment (LCA). Key criteria included energy efficiency, investment costs, fuel production costs, and environmental impacts such as greenhouse gas emissions, acidification, eutrophication, and particulate matter formation. Results indicate that straw bales (L3) and corn stalk chips (L2) offer the most sustainable options, with straw bales demonstrating superior energy efficiency and lower environmental impacts. The VIKOR method, combined with the Entropy Weight Method (EWM), identified straw bales as the optimal supply chain under various weighting scenarios. These findings provide actionable insights for sustainable bioenergy development and policy formulation.

Key words*: agricultural biomass, bioenergy, Life Cycle Assessment, straw, corn stalk, MCDM*

1. Introduction

Biomass represents the most prevalent source of renewable energy in Serbia, as well as in the countries of the Western Balkans, comprising 61% of the estimated 5.65 million tons of renewable energy sources (RES) in the country [1]. Approximately 63% of this biomass is derived from agricultural sources, particularly crop residues such as wheat and corn [1]. In Vojvodina province, over 80% of all harvest residues in crop production are from cereals, primarily wheat and corn, while in Central Serbia, this figure exceeds 84% [2]. These residues hold significant energy potential, with thermal values ranging from 14 MJ/kg to 15 MJ/kg at about 15% moisture content [3]. However, around 75% of these residues are underutilized, often burned in fields, contributing to pollution and resource loss [2]. To enhance the use of crop by-products for renewable energy generation, it is essential to develop technologies for sustainable harvesting and utilization and the production of biomass as well as for biomass production tailored to their specific characteristics and market needs. For example, wheat straw, with a moisture content of 15% to 20%, is suitable for baling, whereas corn stalks, which can contain up to 48% moisture, are not suitable for this process [2]. For the burning of agricultural biomass, special boilers have been developed due to their chemical specificity as well as the form in which the fuels are found [4, 5]. Additionally, adherence to appropriate rules and restrictions in supply logistics is crucial [6].This enables the creation of locally profitable projects for the sustainable use of agricultural biomass in energy production.

Relevant studies emphasize the need for research into biomass supply chains. For example, optimization of biomass supply chains has been studied in various contexts to enhance efficiency and sustainability [7–10]. Research into logistics cost optimization for residual woody biomass supply chains has shown how effective supply chain planning can improve energy yields [11, 12]. Additionally, studies on biomass supply chains from agricultural residues have demonstrated the potential to reduce environmental impacts while improving economic feasibility [13–16].

On the basis of critical literature review, ten criteria are defined for biomass utilization: creation of technical side jobs, preservation of non-renewable energy resources, relative advantage of biofuel production, complexity of biofuel production process, cost of the biomass conversion process, biomass reusability, cost of biomass supply, environmental impacts of biomass accumulation, adaptability of the biofuel production process to the size of biomass production units and the attitude and knowledge of the producers, and energy self-sufficiency of the biomass producer [17].

The selection of the optimal supply chain for residues and fuels from agricultural biomass, including the previously mentioned indicators, requires the application of one of the MCDM (Multi-Criteria Decision Making) methods. In general, MCDM methods have been applied, including energy, manufacturing, transportation, and environmental engineering in a wide range of selected criteria [18]. Some of the supply chains for the production of fuel and energy from biomass have been defined according to the criteria given in the paper [19] as well as the MCDM technique for selecting the optimal supply chain. With this regard, for selecting the optimal supply chain variant for fuels from agricultural residues, the MCDM VIKOR method, together with the entropy method (EWM) was used in this research. The significance of combining the VIKOR and EWM methods in solving engineering problems was also demonstrated in previous researches [20].

Becides, Life Cycle Assessment (LCA) is employed for the environmental impact analysis of the proposed biomass chains, as it is a powerful tool for quantifying the environmental sustainability of products, including bioenergy production [21]. LCA is a frequently used methodology for assessing the environmental impacts of various biomass supply chains, covering different types of biomass, mostly wood biomass and energy crops (perennial grasses, short rotation coppices, etc.) [8], [22], [23–26].

The purpose of the integrated methodology framework combining Life Cycle Assessment (LCA) and Multi-Criteria Decision Making (MCDM) is to create an appropriate tool for evaluating the sustainability of renewable energy systems. This framework provides a set of sustainable indicators, evaluation methods, and objectives applicable to energy policies, electrical supply, and the assessment of various projects [27].

This research aims to achieve three primary objectives: (1) the demonstration of models for the supply of agricultural biomass, taking into account data on agricultural machinery, fuel consumption, electricity, and process productivity; (2) determining the economic and ecological impacts of the studied agricultural biomass supply chains in Serbia; (3) and choosing the optimal supply chain fuel from agricultural residues. A calculation has been conducted based on relevant criteria describing these supply chains to provide new, reliable data specific to Serbia.

2. Methodology

2.1. Selection of Supply chains

The modeling of criteria that encompass fuel production chains from agricultural biomass was performed using a proprietary model. Four agricultural biomass fuel supply chains were analyzed: L_1 - corn stalk pellets, L_2 - corn stalk chips, L_3 - straw bales, and L_4 - straw pellets. The supply chains were described using nine criteria, as follows: energy efficiency - c_1, total investment in supply chains (in EUR) - c_2, price of produced fuel (in EUR/ton) - c_3, greenhouse gasses emissions resulting from use of the fossil fuels during collection, transport and processing of agricultural biomass (in kg CO_2 eq/ton) - c_4, bulk density, which is directly related to the planning of fuel storage (in kg/m^3) - c_5, terrestrial acidification (in kg SO_2 eq/ton) - c_6, marine eutrophication (in kg N eq/ton) - c_7, photochemical oxidant formation (in kg of non-methane volatile organic compound - NMVOC eq/ton) - c_8 and particulate matter formation (in kg PM10 eq/ton) - c_9. The mentioned criteria (c_4, c_6, c_7, c_8, c_9) in the defined set of criteria emerged from the LCA analysis of the considered chains. The conditions under which they are calculated, as well as all input parameters in their calculation, have been defined. The selection of criteria for describing the analyzed chains has been based on a review of previous research [17], [21], [19], [28].

In calculating and defining criteria (c_1, c_2, c_3, and c_5) from the developed model for all four options of agricultural biomass chains, available data relevant to Serbia have been used. Some of the basic input parameters for calculating criteria include: c=1.5 EUR/l for diesel fuel price, r=6 EUR/h for human labor cost per hour, Ce=0.14 EUR/kWh for industrial electricity price, Cr=50 EUR/ton as the initial price of one ton of agricultural biomass. Optimization criteria calculations for supply chains have been performed for a quantity of agricultural biomass up to 6,000 tons, corresponding to the assumption that the transport radius does not exceed 13 km, representing an “working cell” in terms of transport to processing or utilization facilities. For one “working cell”, the amount of agricultural residue that can be collected from an area of approximately 2400 hectares was taken. With an approximate residue yield of 8 tons per hectare and utilization of 1/3 of that same residue from the aforementioned working cell area, approximately 6,000 tons of agricultural residue from straw and corn stalk can be collected. On the other hand, manufacturers of agricultural biomass pelleting lines offer on the market production lines with a maximum capacity of 2 tons per hour, which at full operating capacity does not exceed an annual capacity of 6,000 tons [29].

Pellet transport by truck in this study has been analyzed over a length of 150 km to the end user [30]. The approach to modeling the chains has been based on modeling individual elements that make up a supply chain, whose basic characteristics are given in Table 1. This table provides basic information about the machinery used in all supply chains.

Table 1. Basic elements and characteristics of the use of mechanization in supply chains of agricultural biomass residues

Operation:	**Used machinery:**	**Productivity (ton/h):**	**Fuel and energy consumption (l/h):**	**Polutant emissions (g/t)[1]**
Mowing, wheat harvest	Grain harvester, 200 kW Price: 200 000 EUR [31]	18 tons/h 2,8 ha/h [32]	38 l/h diesel	HC: 3.92; CO: 23.28 NOx: 50.08; PM: 0.26 CO_2: 2,903; CH_4: 0.09 NMHC: 3.82; N_2O: 0.14
Mowing, harvesting corn	Forage harvester, 200 kW Price: 200 000 EUR [31]	12 tons/h 2,8 ha/h [32]	42 l/h diesel	HC: 5.64; CO: 33.52 NOx: 72.11; PM: 0.368 CO_2: 4,180.8; CH_4: 0.136 NMHC: 5.50; N_2O: 0.2
Raking, corn stalk	Tractor (50 kW) + rotary rake; Price: 50 000 EUR [31]	3 tons/h 1,6 ha/h [33]	5,8 l/h diesel	HC: 7.36; CO: 36.66 NOx: 53.90; PM: 0.56 CO_2: 4,212.42; CH_4: 0.17 NMHC: 7.19; N_2O: 0.17
Baling straw, corn stalk	Tractor (50 - 70 kW) + baler; Price: 60 000 EUR [31]	5 tona/h 2 ha/h [34]	14 l/h diesel	HC: 4.46; CO: 22.22 NOx: 32.06; PM: 0.34 CO_2: 2,552.98; CH_4: 0.1 NMHC: 4.36; N_2: 0.1O
Loading/unloading of straw bales, corn stalk	Tractor (50 kW) + front tractor loader Price: 50 000 EUR [31]	5 tons/h 2 ha/h [33]	5 l/h diesel	HC: 4.46; CO: 22.22 NOx: 32.06; PM: 0.34 CO_2: 2,552.98; CH_4: 0.1 NMHC: 4.36; N_2O: 0.1
Transport of bales, (corn stalk, straw)	Tractor (50 kW) + trailer, volume 50 m^3, around 5 tons of loaded bales; Price: 50 000 EUR [31]	5.25 tons/1.93h, length of transport 5 km from the field[2] [33][35]	7 l/h diesel	HC: 12.48; CO: 62.22 NOx: 89.77; PM: 0.95 CO_2: 7,148.34; CH_4: 0.28; NMHC:12.21; N_2O: 0.28
Transport of chopped corn stalk	Tractor (50 kW) + trailer, volume 50 m^3, around 2.5 tons of	2.5 tons/1.53h, length of transport 5 km from the field,	7 l/h diesel	HC: 12.39; CO: 61.72 NOx: 89.06; PM: 0.94 CO_2: 7,091.61; CH_4: 0.28

[1] Poluttant emissions from agricultural machinery operations (hydrocarbons, HC; carbon monoxide, CO; nitrogen oxides, NOx; particulate matter, PM; carbon dioxide, CO_2; methane, CH_4; Nonmethane hydrocarbons, NMHC and nitrous oxide, N_2O) were sourced from the FOEN Non-Road database [49] and adjusted per functional unit, assuming the machinery was manufactured around the year 2000, reflecting the average age of agricultural machinery in Serbia [50].

[2] Emissions calculated by the duration of transport from the field to the pellet plant taking into account a distance of 5 km and an average speed of the tractor of 25 km/h.

	chopped corn stalk chips Price: 75 000 EUR [31]	[36]		NMHC:12.11;N_2O: 0.28
Pelleting, corn stalk, straw	Pellet plant, 1 ton/h. Max power: 226.9 kW [29] Price: 215 000 EUR [31]	1 ton/h	Corn: about 197 kWh/ton, electricity [37] Straw: about 170 kWh/ton, electricity [37]	NOx: 1; PM: 0.26 CO_2: 1,000; SO_2: 14[3]
Forklift loading/unloading pellets	Power: 55 kW, Price: 15 000 EUR [31]	40 tons/h [38]	6 l/h diesel	HC: 0.46; CO: 2.32 NOx: 3.35; PM: 0.035 CO_2: 282.71; CH_4: 0.01 NMHC: 0.46; N_2O: 0.01
Pellet transport, truck	Truck up to 20 t, allowed load. Price: 100 000 EUR [31]	20 tons, transport length up to 150 km	40 l/100 km with load, 32 l/100 km no load, diesel	CO: 0.19[4]; NOx: 0.03 PM: 0.02; CO_2: 118.69 NMHC: 0.03

The estimated hourly diesel fuel consumption values for agricultural and other machinery engines were calculated according to [39]:

$$F_C = P \cdot 0{,}2925 \cdot k \tag{1}$$

Where: P is the power of the machine in kW, and k is the machine load factor in kg/kWh, which ranges from 0.2 to 0.8 for different agricultural operations [40].

The yield of wheat or straw, corn or corn stalk is highly variable, ranging from 5 to 7 tons of wheat per hectare and 5 to 11 tons of corn per hectare [41, 42]. The assumption has been adopted that the residue index in cereals such as wheat and corn is approximately equal, which is also applied to agricultural biomass residues in the form of straw or corn stalk. The removal of harvest residues without depleting the soil of nutrients is done at a rate of 1/3 of the total available harvest residue [43].

2.2. Development of Model for Utilization of Agricultural Residues

The selection of supply chains analyzed in the model considers resource diversity, bulk density of fuels, various logistics, investment, and other implementation possibilities of the mentioned supply chains. Figure 1. provides a detailed schematic of the basic logistical operations for the production of corn stalk pellets, corn stalk chips, straw bales, and straw pellets.

Considering the specified quantity of 6,000 tons of biomass within one “working cell” (i.e., the area where agricultural residue is collected), this value serves as a constraint for the economic feasibility of biomass collection and transport processes [29]. It is assumed that the collection and processing of these 6,000 tons of agricultural residue can be completed within three months. Accordingly, calculations have been made for the required number of machinery and devices based on their unit capacities and

[3] The emissions refer to emissions during the burning of coal in thermal power plants, which contribute 70% to the production of electricity in the RS.

[4] Pollutant emissions from Ecoinvent 3 process „Transport, freight, lorry 16-32 metric ton, EURO3 {RER}| transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def, U“.

characteristics, as detailed in Table 1. The number of components for participation in all chains includes: forage harvester 1 pcs, grain combine harvester 1 pcs, rotary rakes and tractors 3 pcs, tractor and baler for straw or corn stalk 2 pcs, tractor and front loader 2 pcs, tractor and trailer for bales 4 pcs, tractor and trailer for chopped corn stalk transport 6 pcs, pellet plant for straw or corn stalk 2 pcs, forklift 1 pcs, and truck for pellet transport 1 pcs. Total investments in agricultural residue supply chains have been calculated based on the obtained values.

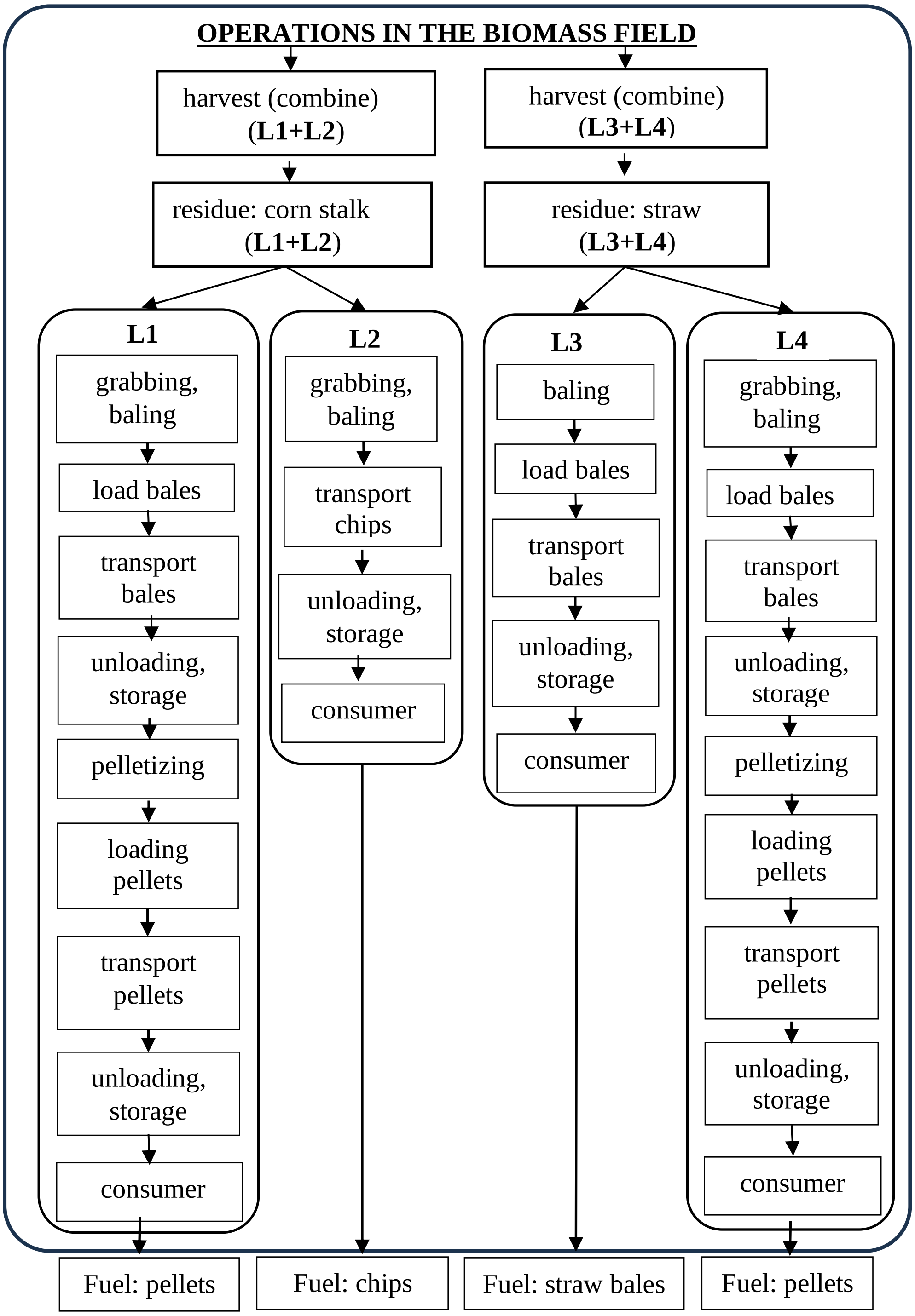

Figure 1. Agricultural biomass utilization scheme, solid fuels supply chains

The modeling of the chains has been carried out under the assumption that agricultural biomass (corn stalk or straw) is first collected through harvesting operations. In chains L_1, L_3, and L_4, the operations following harvest include raking, baling, loading, transportation, and unloading. Baling of agricultural biomass is performed to facilitate the handling of biomass during collection, transportation, storage, and automated combustion processes [44]. In chains L_1 and L_4, it is assumed that the bales are transported to a pelletizing facility where the pelletizing process occurs, and the finished product is then transported by truck to the final consumer. In chain L_3, the process ends with the transportation of baled biomass to a facility and storage as ready fuel. In chain L_2, the corn stalk is chopped into chips and then collected directly into a tractor trailer that follows a forage harvester after which it is transported directly to the final consumer. An optimal transport distance for biomass in the model is considered to be around 13 km [45]. This generally means that approximately 8 km of biomass collection occurs in the field, and the transport distance from the field to storage is about 5 kilometers. The characteristics of agricultural residues used in the model are provided in Table 2 and were sourced from the literature [3].

Table 2. Characteristics of fuel from agricultural residues

Characteristics	Pellet of corn stalk	Chips of corn stalk	Straw bales	Straw pellets
Moisture	12 %	15 %	15 %	12 %
Lower heating value (LHV)	15.4 MJ/kg	14.8 MJ/kg	14.4 MJ/kg	15 MJ/kg
Bulk density	670 kg/m^3	50.9 kg/m^3	150 kg/m^3	670 kg/m^3
Dimensions: d, L	d=6-10 mm, L=5-30 mm	2.5 do 5 cm	1.5 x 1 x 0.75 m	d=6-10 mm, L=5-30 mm

2.2.1 Calculation Ranking and Optimization of the Supply Chains

After calculating all the criteria for the mentioned chains, they were compared and ranked. The ranking and optimization of the supply chains have been performed by using the VIKOR method [46]. The VIKOR method generates a compromise ranking list and the identifies the solution closest to the ideal outcome, interrupted by the value Q_i for multi-criteria ranking of the alternatives. Generally, a lower Q_i value for an alternative means it is closer to the ideal solution. The VIKOR includes verification options: acceptable advantage and acceptable stability, which provide feedback on achieving a compromise solution by adjusting the weights derived from selected criteria to ensure the conditions of stability and acceptable advantages of the solution for multi-criteria ranking [46]. The calculation of weight coefficients for the adopted criteria was performed by using the objective EWM [47], which addresses uncertainty in the information structure of the decision matrix, known as Shannon's entropy [48]. The entropy value ranges from 0 to 1; a higher E_i value signifirs a greater the degree of differentiation for the index i, thus assigning it more weight. The information contained in the normalized decision matrix emitted by each criterion f_i can be measured as the value of entropy E_i. The results of the optimal supply chain selection have been confirmed even in the case of equal importance of all criteria in the multi-criteria optimization process.

2.3 LCA of Agricultural Biomass Chains

2.3.1. Goal, scope and system boundaries

The primary goal of the study is to analyse the environmental impacts of various agricultural operations for collecting and processing of agricultural residues for bioenergy. According to system boundaries a “gate-to-gate” approach was used, including the analysis of all inputs and outputs from the collection of biomass onwards, including further processing into pellets, chips, or bales and subsequent transport to the end consumer. The production of used machinery and infrastructure has not been included within the system boundaries.

The functional unit used was 1 ton of dried biomass (at 15% moisture content). Inputs included fuels (liquid fossil fuels and electricity) for biomass processing machinery, while outputs included emissions to the atmosphere from biomass processing. For the LCA of the observed chains SimaPro version 8.0.4.7. software is used.

2.3.2. Inventory analysis

Input data used for the analysis is presented in Table 1. Main inputs for the machinery used and productivity are taken from literature [29], [31–38]. Poluttant emissions from agricultural machinery operations (hydrocarbons, HC; carbon monoxide, CO; nitrogen oxides, NOx; particulate matter, PM; carbon dioxide, CO_2; methane, CH_4; Nonmethane hydrocarbons, NMHC and nitrous oxide, N_2O) were sourced from the FOEN Non-Road database [49] and adjusted per functional unit, assuming the machinery was manufactured around the year 2000, reflecting the average age of agricultural machinery in Serbia [50].

Emissions from pelletizing operations have been based on emissions from electricity generation, specifically emissions from coal combustion in thermal power plants, which constitute 70% of electricity production in the Republic of Serbia, with an annual production of 24,360 GWh [51]. Emissions of harmful substances during the transport of bales and chips from the field were calculated based on the time required for this transport. Considering a tractor with a trailer travels approximately 13 km at an average speed of 9 km/h, the transport time for bales and chips from the field is estimated at about 1 hour. For pellet transport by truck, a modified process from the Ecoinvent 3 database has been used (Transport, freight, lorry 16-32 metric ton, EURO3 | Alloc Def).

2.3.3. Impact assessment

For the impact assessment, the ReCiPe 2016 v1.11 “Midpoint” method was used [52]. The ReCiPe method is a life cycle impact assessment (LCIA) framework that evaluates environmental impacts across various categories at both midpoint and endpoint levels. Chosen categories for the impact assessment of the analysed chains are *climate change*, *terrestrial acidification*, *marine eutrophication*, *photochemical oxidant formation*, and *particulate matter formation*, as these are the categories where environmental impacts have been observed. Pollutant emissions from the life cycle of agricultural chains have been converted into appropriate equivalents for each impact category based on predefined conversion factors and characterizations in the SimaPro software and ReCiPe Method [52, 53].

3. Results

3.1. Results from the Developed Model

Results of criterion calculations (c_1, c_2, c_3, and c_5) from the developed model are provided in the Table 3. For calculating the price of fuel, a reference price of 50 EUR/ton was assumed for biomass, with a moisture content of 15%.

Table 3. Results of criteria calculation (c_1, c_2, c_3 and c_5) for all 4 chains of agricultural biomass

Impact category	Unit	L_1	L_2	L_3	L_4
Energy efficiency, c_1	no unit	0.75	0.96	0.94	0.79
Total investment in supply chains, c_2	EUR	1,430,000	650,000	940,000	1,500,000
Price of produced fuel, c_3	EUR/ton	138.87	65.85	70.45	127.55
Bulk density, c_5	kg/m^3	670	50.9	150	670

According to Table 3, chain L_2 exhibits the highest energy efficiency among the supply chains, along with the lowest investment in the chain itself and the lowest cost per ton of corn stalk chips produced. However, the bulk density of corn stalk chips is the lowest, nearly three times lower than that of baled straw. This means that storing corn stalk chips would require storage facilities nearly three times larger than those needed for baled straw, thereby increasing storage investment. Considering this contrast in bulk density alongside other criteria in the analysis, as well as additional criteria from the LCA analysis, the importance of applying MCDM analysis in selecting the optimal supply chain becomes crucial.

3.2. LCA

The results of the LCA for all four chains are presented in Table 4.

Table 4. LCA results for all 4 chains of agricultural biomass

Impact category	Unit	L_1	L_2	L_3	L_4
Climate change, c_4	kg CO_2 eq/ton	179.16	15.56	19.18	156.27
Terrestrial acidification, c_6	kg SO_2 eq/ton	2.34	0.12	0.15	2.02
Marine eutrophication, c_7	kg N eq/ton	0.02	0.01	0.01	0.02
Photochemical oxidant formation, c_8	kg NMVOC eq/ton	0.84	0.24	0.29	0.74
Particulate matter formation, c_9	kg PM10 eq/ton	0.54	0.05	0.06	0.47

Given the greater complexity of biomass pellet production chains (L_1 and L_4), these chains exhibit the highest environmental impacts across all analyzed impact categories, particulary in the *climate change* category. Peletizing agricultural residues contributes 76 % of the total impact in the this category for both L_1 and L_4 chains, primarily due to the electricity used, which is predominantly generated from coal combustion in thermal power plants (accounting for 70 % of total electricity production in Serbia). The results indicate that the environmental impacts are 13.6 % higher in the L_1 chain compared to the L_4 chain, primarily due to the greater electricity consumtion required to pelletize 1 ton of corn compared to 1 ton of straw (197 kWh vs. 170 kWh, Table 1). Transportation of pellets by truck is the next operation with the highest environmental impact is the *climate chang*e category, contributing 10 % of the total impacts. This is attributed to the long transport distance (150 km) from the pellet plant to the final consumer. Across all other impact categories, impact are 12 %-14 % higher in L_1 chain compared to L_4 chain. In contrast, the L_2 and L_3 chains show lower environmental impacts across all analysed categories compared to L_1 and L_4 chains. However, the L_3 chain exhibits approximately 20 % higher impact in all analysed categories compared to L_2 chain due to its greater complexity, as it involves more operations. Among agricultural activities for collecting and preparing agricultural biomass, harvest operations have the greatest environmental impact. This is primarily due to the use of higher-powered agricultural machinery, such as forage and harvest combines with 200 kW power, compared to tractors with 50-70 kW power.

3.3. VIKOR and Entropy Method for Optimal Selection of Biomass Fuel Supply Chains

The decision matrix for the analyzed biomass fuel supply chains is contained in Tables 3 and 4, which include 9 criteria and rank 4 observed chains. The process of ranking and selecting the optimal supply chain was conducted using the VIKOR method [19], [20], [46], [47]. In accordance with the objective EWM method [47] the weights of the criteria were determined from the information structure given in Tables 3 and 4. The weight values of the adopted criteria for comparing biomass supply chains are presented in Table 5. Positive criteria are marked with (+) for maximization, while negative criteria are marked with (-) for minimization. According to the results obtained from the EWM method, the highest weight values were assigned to criteria: c_6, c_4, c_9, and c_5, in a descending order.

Table 5. Weight of criteria determined by EWM method for observed biomass chains

Name of criteria	Type	Weight
Energy efficiency c_1	(+ maximization)	0.003
Investment c_2	(- minimization)	0.027
Price per ton c_3	(- minimization)	0.029
Carbon dioxide eq. emissions c_4	(- minimization)	0.207
Bulk density c_5	(+ maximization)	0.174
Terrestrial acidification c_6	(- minimization)	0.256
Marine eutrophication c_7	(- minimization)	0.03
Photochemical oxidant formation c_8	(- minimization)	0.071
Particulate matter formation c_9	(- minimization)	0.202

3.4 Analysis of the results of optimization of agricultural biomass supply chains

The optimization results in the combined use of VIKOR-EWM methods indicate that the final optimal alternatives are: L_3- straw bales and L_2- corn stalk chips chains.

The ranking results by using the VIKOR method for the observed supply chains indicate that baled straw (chain L_3), represents the optimal solution for utilization. The optimal chain L_3, is characterized by the following criteria:: energy efficiency c_1=0.936694568, total investment in supply chains c_2=940,000 EUR, price of produced fuel c_3=70.45 EUR/ton, climate change c_4=19.18 kg CO_2 eq/ton, bulk density c_5=150 kg/m3, terrestrial acidification c_6=0.15 kg SO_2 eq/ton, marine eutrophication c_7=0.01 kg N eq/ton, photochemical oxidant formation c_8=0.29 kg NMVOC eq/ton, particulate matter formation c_9=0.06 kg PM10 eq/ton.

Following baled straw, shredded corn stalk is the next best alternative. The primary difference between the supply chains for baled straw and corn stalk chips lies in the bulk density of the produced fuel (150 kg/m^3 and 50.9 kg/m^3, respectively). The lower bulk density of corn stalk chips necessitates larger storage volumes, requiring three times more space than baled straw, which directly affects investment size in the supply chain. Althoug chain L_2 has the lowest basic value of the investment and the lowest value of the LCA criteria, its storage requirements pose significant challenges.

In a second analysus for selecting the optimal fuel supply variant from agricultural biomass, equal weights were asigned to all criteria ($c_1= c_2= c_3= c_4= c_5= c_6=c_7=c_8=c_9=1/9$). This optimization process again identified L_3- straw bales as the final alternative. Both analyses with different sets of weighting schemes consistently indicates that straw bales are the optimals supply variant. The stability analysis provided by the VIKOR method and the prior variation of the importance of weight factors (EWM method and equal weighting of criteria), confirmed the L_3 (baled straw) as the top-ranked option.

In cases where biomass production is self-owned, meaning the biomass resource is not purchased, the production of these fuels is economically more viable and competitive. In such cases, grain production can be integrated with biomass fuels production. The estimated cost are approximately 20 EUR/ton for collecting and baling straw, slightly under 20 EUR/ton for the shredded corn stalk, leading to production costs of pellets from these residues being under 100 EUR/ton. However, a significant barrier remains in organizing agricultural residue supply chains due to the high initial investment in equipment, facilities, and storage.

One advantage of MCDM methods such as VIKOR is their ability to integrate with other techniques, enhancing flexiblity in multiple methods. In this context, MCDM has been combined with LCA method [54] to develop a new approach that considers technical, economical and environmental criteria for improved planning and management of agricultural residue supply chains.

4. Conclusion

This paper presents a review and comparison of straw and corn stalk agricultural residue supply chains for bioenergy generation, focusing on four distinct supply chains relevant to conditions in Serbia. In this research were obtained: a model for supplying agricultural residue in the form of fuels was developed; the environmental (LCA impact) and economic impact on agricultural residue supply chains was determined; and the optimal supply chain utilizing straw bales as fuels was identified.

The employed MCDM methodology, specifically VIKOR and Entropy method, along with with LCA analysis revealed that agro-pellets production chains have a significantly negative environmental impact, which positions them as less favourable option for utilization. This conclusion certainly does not reduce the importance of their use; rather it highlights the problem of the substantial electricity consumption in the pellet production process, 70 % of which is fossil-based. On the other hand, the production of chips from agricultural residue demonstates a significantly lower LCA impact. Furthermore, when selecting the optimal supply chain by VIKOR with equally weighted criteria compared to weights derived from the EWM method, both approaches yielded the same ranking solution for baled straw as fuel. This consistency reinforces the stability of the solution.

For further research, it is crucial to explore and compare supply chains from various resource categories, such as: forest biomass, agricultural biomass and energy crops by using a combined MCDM and LCA methodology. Such analysis should focus on two categories of solid fuels from biomass, chips and pellets. This approach will not only facilitate the optimal selection of supply chains but also identify which biomass chains have the lowest environmental impact.

Acknowledgment

The authors acknowledge the support of the European Research Executive Agency (REA) for funding this research under the project "ENPOWER – Enhancing Scientific Capacity for Energy Poverty (101160253 — ENPOWER — HORIZON-WIDERA-2023-ACCESS-02)".
The authors acknowledge the support of the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, Project No. 451-03-65/2024-03/200105, Faculty of Mechanical Engineering, University of Belgrade and Project No. 451-03-66/2024-03/200213, Innovation Center of the Faculty of Mechanical Engineering in Belgrade.

References

[1] Republika Srbija, M. rudarstva i energetike, Strategija razvoja energetike republike Srbije do 2025. sa projecijama do 2030., 2015
[2] Tica, N., et al., Izveštaj projekta: Mogućnosti i ekonomski aspekti upotrebe žetvenih ostataka za proizvodnju toplotne energije (Project report: Possibilities and economic aspects of using of agricultural residues for heat production), Novi Sad, 2015
[3] Society, G.S.E., & Ecofys., *Planning And Installing Bioenergy Systems A Guide For Installers, Architects And Engineers*, 2004
[4] Turanjanin, V.M., et al., Development Of The Boiler For Combustion Of Agricultural Biomass By Products, *Thermal Science*, *14* (2010), 3, pp. 707-714
[5] Marinković, A.D., et al., POLYCYCLIC AROMATIC HYDROCARBONS EMISSION FROM CIGAR BURNER COMBUSTION SYSTEM AND COMPARISON OF THEIR CONTENT IN FLY ASHES, *Thermal Science*, *26* (2022), 6, pp. 4749-4761
[6] Martinez-Valencia, L., et al., Biomass supply chain equipment for renewable fuels production: A review, Biomass and Bioenergy, Volume 148, (2021).
[7] Nunes, L.J.R., Silva, S., Optimization Of The Residual Biomass Supply Chain: Process Characterization And Cost Analysis, *Logistics*, *7* (2023), 3
[8] Vatsanidou, A., et al., A Life Cycle Assessment Of Biomass Production From Energy Crops In Crop Rotation Using Different Tillage System, *Sustainability (Switzerland)*, *12* (2020), 17
[9] Lijó, L., et al., Life Cycle Assessment Of Renewable Energy Production From Biomass : The Italian Experience, in: *Green Energy and Technology*, Springer Verlag, 2019, pp. 81-98
[10] Sun, O., Fan, N., A Review on Optimization Methods for Biomass Supply Chain: Models and Algorithms, Sustainable Issues, and Challenges and Opportunities, Process Integr Optim Sustain **4**, 203–226 (2020). https://doi.org/10.1007/s41660-020-00108-9
[11] Mann, M.K., Spath, P.L., Life Cycle Assessment Of A Biomass Gasification Combined-Cycle System, *Fuel and Energy Abstracts*, *2009* (1997), Journal Article, pp. 100
[12] Wang, C.N., et al., Bi-Objective Optimization Modeling For Biomass Supply Chain Planning, *Measurement and Control (United Kingdom)*, (2024)

[13] Huy Nguyen, D., Study on biomass supply chain planning and inventory control of perishable products, Other. Université de Technologie de Troyes, 2019. English. ffNNT : 2019TROY0005ff. fftel-03615104f, (2022).

[14] Yu, Z., et al., Review in life cycle assessment of biomass conversion through pyrolysis-issues and recommendations, Green Chemical Engineering, Volume 3, Issue 4, (2022), Pages 304-312, ISSN 2666-9528.

[15] Helal, M.A., et al., A Review of Biomass-to-Bioenergy Supply Chain Research Using Bibliometric Analysis and Visualization, MDPI, 2023.

[16] Osman, A.I., et al., Conversion of biomass to biofuels and life cycle assessment: a review. Environ Chem Lett 19, 4075–4118 (2021).

[17] Firouzi, S., et al., Hybrid Multi-Criteria Decision-Making Approach To Select Appropriate Biomass Resources For Biofuel Production, *Science of the Total Environment*, *770* (2021)

[18] Štilić, A., Puška, A., Integrating Multi-Criteria Decision-Making Methods with Sustainable Engineering: A Comprehensive Review of Current Practices, Multidisciplinary Digital Publishing Institute (MDPI) (2023).

[19] Vasković, S., et al., Energy Chains Optimization For Selection Of Sustainable Energy Supply, in: *Sustainable Supply Chain Management*, InTech, (2016).

[20] Mrkić-Bosancic, M., et al., OPTIMIZATION OF ENERGY MIX AND POSSIBILITIES OF ITS APPLICATION IN ENERGY TRANSITION USING MULTICRITERIA APPROACH, Thermal Science, (2023), 27, 3, pp 2501. 2512.

[21] Hosseinzadeh-Bandbafha, H., et al., Life cycle assessment of bioenergy product systems: A critical review, Advances in Electrical Engineering, Electronics and Energy, Volume 1, (2021).

[22] Perić, M., et al., Life Cycle Assessment Of Wood Chips Supply Chain In Serbia, *155* (2020), pp. 1302-1311

[23] Ma, Y., et al., The Economic Feasibility And Life Cycle Carbon Emission Of Developing Biomass-Based Renewable Combined Heat And Power (RCHP) Systems, *Fuel*, *353* (2023), pp. 129177

[24] Perić, M., et al., Life Cycle Impact Assessment Of Miscanthus Crop For Sustainable Household Heating In Serbia, *Forests*, *9* (2018), 10

[25] Peric, M.M., et al., Diesel Production By Fast Pyrolysis Of Miscanthus Giganteus, Well-Topump Analysis Using The Greet Model, *Thermal Science*, *2018* (2018)

[26] Alejandro Perdomo, E.E., et al., Life Cycle Assessment Of Agricultural Wood Production-Methodological Options: A Literature Review. Bioenerg. Res. 14, 492–509 (2021).

[27] Campos-Guzmán, V., et al., Life Cycle Analysis with Multi-Criteria Decision Making: A review of approaches for the sustainability evaluation of renewable energy technologies, Renewable and Sustainable Energy Reviews (2019), 104, issue C, p. 343-366.

[28] Vasković, S., et al., Multi-Criteria Optimization Concept for the Selection of Optimal Solid Fuels Supply Chain from Wooden Biomass, (2015)

[29] ***, https://www.propelety.com/pellet-line/,

[30] Kwaśniewski, D., Logistic And Economical Preconditions For Production Of Pellets From Sawdust, *Agricultural Engineering*, *23* (2019), 2, pp. 5-14

[31] ***, https://tehmago.co.rs/category/poljoprivredne-masine-i-oprema,

[32] Đević, M., et al., Modern Wheat Combine Claas Lexion 450 In Corn And Wheat Harvesting, *Agric Technol (Thail)*, *28* (2004), 1, pp. 27-40
[33] Bavrka, I., Ekonomska opravdanost korištenja žetvenih ostataka za unaprjeđenje dohotka, Diplomski rad, Univerzitet u Zagrebu, Poljoprivredni fakultet (2017).
[34] Comer, K., C.T., BALES (Biomass Alliance for Logistics Efficiency and Specifications) Project Overview and Harvest Data Collection Progress, Plans, and Issues, 2015
[35] Potkonjak, V., Zoranović, M., Collection, Transport And Storage Of Straw Bales., *Contemporary agricultural technology*, *31* (2005), 4, pp. 204-210
[36] Theerarattananoon, K., et al., Physical Properties Of Pellets Made From Sorghum Stalk, Corn Stover, Wheat Straw, And Big Bluestem, *Ind Crops Prod*, *33* (2011), 2, pp. 325-332
[37] Sokhansanj, S., T.A., T.S., & M.S., Integrating Biomass Feedstock With An Existing Grain Handling System For Biofuels., *ASABE (2006) Paper No. 06618 . St. Joseph, Mich.*, (2006)
[38] Zajac, P., Rozic, T., Energy Consumption Of Forklift Versus Standards, Effects Of Their Use And Expectations, *Energy*, *239* (2022)
[39] Krmpotić T., Kiš A., Total Costs Of Agricultural Machinery, *Agric Technol (Thail)*, *30* (2005), 2, pp. 105-114
[40] Savin, L., Optimization of the Structure of the Machine Pool at Field Crops Production, Ph. D. thesis, University of Novi Sad, Faculty of Agriculture, (2004).
[41] ***, EUROSTAT, 2019
[42] Mariotti, M., et al., The Analysis Of Wheat Yield Variability Based On Experimental Data From 2008-2018 To Understand The Yield Gap, (2021)
[43] Tarkalson, D.D., et al., Impact Of Removing Straw From Wheat And Fields: A Literature Review, *Better Crops*, *93* (2009), 3, pp. 17-19
[44] Guerrieri, A.S., et al., Study Of A Large Square Baler With Innovative Technological Systems That Optimize The Baling E_ectiveness, *Agriculture (Switzerland)*, *9* (2019), 5
[45] Suardi, A., et al., Economic Distance To Gather Agricultural Residues From The Field To The Integrated Biomass Logistic Centre: A Spanish Case-Study, *Energies (Basel)*, *12* (2019), 16
[46] Opricovic, S., Tzeng, G.H., Compromise Solution By MCDM Methods: A Comparative Analysis Of VIKOR And TOPSIS, *Eur J Oper Res*, *156* (2004), 2, pp. 445-455
[47] Dang, V.T., Dang, W.V.T., Multi-Criteria Decision-Making In The Evaluation Of Environmental Quality Of OECD Countries: The Entropy Weight And VIKOR Methods, *International Journal of Ethics and Systems*, *36* (2020), 1, pp. 119-130
[48] Mi, J., et al., A Method Of Entropy Weight Quantitative Risk Assessment For The Safety And Security Integration Of A Typical Industrial Control System, *IEEE Access*, *9* (2021), pp. 90919-90932
[49] FOEN, Non road emissions database, http://www.bafu.admin.ch/luft/00596/06906/offroad-daten/index.html?lang=en
[50] Radivojević, D., Popis poljoprivrede 2012-Poljoprivredna mehanizacija, oprema i objekti (Census of Agriculture 2012-Agricultural machinery, equipment and facilities), Beograd, 2014
[51] *https://ers.ba/
[52] Huijbregts, M.A.J., et al., ReCiPe 2016 v1.1 A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization, 2017

[53] Goedkoop, M., et al., ReCiPe 2008. A LCIA method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation, 2013

[54] Theilig, K., et al., Life Cycle Assessment And Multi-Criteria Decision-Making For Sustainable Building Parts: Criteria, Methods, And Application, *International Journal of Life Cycle Assessment*, (2024)

Submitted: 20.08.2024.
Revised: 22.01.2025.
Accepted: 27.01.2025.