Environmental and Climate Technologies
2025, vol. 29, no. 1, pp. 851–864
https://doi.org/10.2478/rtuect-2025-0057
https://content.sciendo.com

Sustainability Trade-offs in Biochar Production

Valerija KOSTEVICA[1*], Anna KUBULE[2], Ilze VAMZA[3], Toms IRBE[4], Marika ROSA[5], Dagnija BLUMBERGA[6]

[1–6]*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, Riga, LV-1048, Latvia*

Received 01.08.2025; accepted 08.10.2025

***Abstract* – Biochar production and application offer a promising strategy for carbon sequestration and soil improvement, yet the sustainability of different production technologies and feedstock remains underexplored. This study applied multi criteria analysis (MCDA) using TOPSIS method to evaluate 12 biochar production scenarios. Four indicator categories were used – environmental, economic, technological, agronomic. The results show that low temperature pyrolysis using herbaceous sources as feedstock consistently ranked highest, due to lowest production costs, high yield and strong agronomic performance. Biosolids (sludge – derived organic material) based scenarios performed best when agronomic indicators were prioritized. Overall, scenarios with higher temperature regime showed lowest ranking, due to lower biochar yield and crop productivity impact. The results highlight the importance of the synergy between feedstock and temperature regime in determining biochar sustainability. The sensitivity analysis demonstrates that scenario ranking is highly dependent on decision making priorities, underscoring the need for context specific assessment.**

***Keywords* – Biochar; carbon; climate actions; MCDA; sequestration; sustainable consumption and production.**

1. INTRODUCTION

Based on the Green Deal strategy [1] and the European Climate law [2] Europe must reach climate neutrality by 2050 and reduce GHG emissions by 55 % compared to 1990. According to the Regulation (EU) 2018/841 [3] LULUCF sector can help achieve these goals because it is an important source of raw materials for other industries and is capable of both preventing GHG emissions and sequestering carbon in its ecosystems, thus offsetting emissions from other industries, where it is much more complicated to reduce them. According to the National Energy and Climate plan 2021–2030 (NECP), Latvia has good potential for CO_2 capture, due to the large area of forests (53.63 % of the total country area) and agriculture land (34.91 % of the total country area) [4]. Since 1990 net removals in LULUCF in Latvia have reduced by 140 %, due to an increase in harvesting rate and aging of forest, but in agriculture, GHG emissions have lowered by 55 %, due to a decrease in the livestock and sown areas [5]. According to the baseline scenario, by 2030 Latvia must achieve the net sequestration in the LULUCF (−644 kt CO_2 eq. in 2030 while in 2022 net emissions were 4944.2 kt CO_2 eq.) and lower emissions in agriculture (2176.33 kt CO_2 eq. in 2030, while in 2022 net emissions were 2253.83 kt CO_2 eq.) [4]. As Latvia has high potential for CO_2 sequestration, one of the possible approaches to reduce GHG emissions is the use of carbon dioxide removal (CDR) technologies, where the main aim is to capture and store CO_2 in long term [6], [7]. Many CDR

* Corresponding author.
E-mail address: Valerija.Kostevica@rtu.lv

technologies exist, grouped into three main categories: ocean, technological and biological [8].

To reach Latvia's LULUCF emissions goal, NECP 2021–2030 [4] has indicated policies and measures that should be implemented. One of the measures considered is the use of biochar in agricultural lands. Use of biochar as a CDR technology and for soil improvement is widely acknowledged, because biochar is considered as a stable matter and can stay in soil from 100 to 1000 years with minor CO_2 losses to the atmosphere [9], [10]. Biochar is a carbon-containing material, which is made industrially by using thermochemical conversion, and is co-produced with syngas and biooil, with share dependent on the applied technology. The physiochemical properties of biochar depend mainly on the used technology, reaction temperature and organic material which is used for production (feedstock) [11], [12]. Biochar can be produced using one of the following technology processes - gasification, pyrolysis, torrefaction and hydrothermal carbonization (HTC). Wide range of feedstock can be utilized – wood, agriculture waste, wood waste, manure or biosolids. Due to large surface area, high porosity and generous oxygen-containing functional groups [13], biochar can be considered as a good pollution removal, soil amendment technology and carbon sequestration technology [14]. When biochar is produced from sewage sludge or the organic matter of urban waste, it must be considered that this biomass can saturate high concentrations of heavy metals or other toxic chemicals, which limit biochar use as soil amendment technology [14], [15].

According to the study by Lefebvr *et al*. [16] Latvia has one of the highest biochar CO_2 removal potential in Europe expressed as a percentage of total GHG emissions generated by country (15–20 %). The growing policy support for biochar coincides with the methodological advancements that support its inclusion in national GHG inventory report as a carbon sink source. In 2019 IPCC introduced refinement to the 2006 IPCC Guidelines, where the method for estimation of changes in mineral soil organic carbon stocks due to biochar amendment was described [17]. This guideline allows to evaluate the stored carbon from biochar amendment using Tier 1 methodology. Given Latvia's high potential for biochar-based carbon sequestration and its recognition in national policy framework, there is a need to evaluate which biochar production pathway offers most sustainable performance. Therefore, this study aims to compare 12 biochar production scenarios using MCDA approach, by incorporating indicators and sensitivity analysis to identify most suitable technology-feedstock combinations.

2. METHODOLOGY AND DATA

This study applies MCDA approach using TOPSIS method to evaluate 12 different combinations of technology and feedstock used to produce biochar. The technologies considered: slow pyrolysis (for low, medium and high temperature) and gasification (high temperature). Each technology was assessed for three different feedstock types: woody biomass, herbaceous biomass, and biosolids (sewage sludge) (see Table 1). Feedstock and technology selection were based on the IPCC update in 2019, which introduced: *Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development* [17]. In this refinement Tier 1 values for organic carbon content factor of biochar by production type and feedstock were provided. In total IPCC provides values for six different feedstocks. For this study only three feedstocks that are the most common in Latvia were chosen.

TABLE 1. COMBINATIONS OF THERMOCHEMICAL TECHNOLOGIES AND FEEDSTOCK TYPES EVALUATED IN THE STUDY

Nr	Production Process	Feedstock	Production Temperature	Used abbreviation in study
1	Pyrolysis	Wood	High temperature pyrolysis (> 600 °C)	HP-W
2	Pyrolysis	Herbaceous (grasses, forbs, leaves; excluding rice husks and rice straw)	High temperature pyrolysis (> 600 °C)	HP-H
3	Pyrolysis	Biosolids (paper sludge, sewage sludge)	High temperature pyrolysis (> 600 °C)	HP-B
4	Pyrolysis	Wood	Medium temperature pyrolysis (450–600 °C)	MP-W
5	Pyrolysis	Herbaceous (grasses, forbs, leaves; excluding rice husks and rice straw)	Medium temperature pyrolysis (450–600 °C)	MP-H
6	Pyrolysis	Biosolids (paper sludge, sewage sludge)	Medium temperature pyrolysis (450–600 °C)	MP-B
7	Pyrolysis	Wood	Low temperature pyrolysis (350–450 °C)	LP-W
8	Pyrolysis	Herbaceous (grasses, forbs, leaves; excluding rice husks and rice straw)	Low temperature pyrolysis (350–450 °C)	LP-H
9	Pyrolysis	Biosolids (paper sludge, sewage sludge)	Low temperature pyrolysis (350–450 °C)	LP-B
10	Gasification	Wood	High temperature gasification (> 600 °C)	G-W
11	Gasification	Herbaceous (grasses, forbs, leaves; excluding rice husks and rice straw)	High temperature gasification (> 600 °C)	G-H
12	Gasification	Biosolids (paper sludge, sewage sludge)	High temperature gasification (> 600 °C)	G-B

2.1. Selection of Indicators and Data Collection

To evaluate 12 biochar production scenarios using the TOPSIS method the following indicator categories were selected – environmental, economic, technological and agronomic. Indicator selection was based on peer-reviewed literature and availability of data for each of the scenarios.

For the environmental indicator category two indicators were selected: carbon sequestration potential (t CO_2 eq/ t biochar) and biochar carbon content (% C). These indicators emphasize the biochar role as a CDR technology and its contribution to long-term climate mitigation [18], [19]. Biochar carbon content indicator was selected because it acts as a measurable proxy for the long-term carbon stability of biochar and its capacity as carbon sink. Although carbon sequestration depends on many factors, carbon content shows how much of carbon is stored in solid and stable form [20]. Data for biochar carbon content were retrieved from peer-reviewed scientifical articles reporting experimental values of % C for different feedstock and pyrolysis conditions (Table 2). Carbon sequestration potential was calculated using the IPCC 2019 refinement Appendix 4 equation 4AP.1, which provides the methodology on how to calculate carbon sequestrated in mineral soils for biochar amendment (tons sequestered C yr^{-1}). The calculations use TIER 1 values for organic carbon content of biochar by production type/feedstock and values for fraction of biochar carbon remaining after 100 years [17]. For all 12 scenarios functional unit was 1 ton of biochar stored in the soil. After the calculations were performed, all values were converted to from t C to t CO_2. Table 2 shows calculated amount of sequestrated CO_2 from one ton of biochar for each scenario.

TABLE 2. INDICATORS AND REFERENCE VALUES USED IN THE MCDA EVALUATION IN THIS STUDY

Technology – feedstock combination	Environmental		Economic		Technological		Agronomic
	Carbon sequestration potential[1]	Biochar carbon content	Profit per ton CO_2 eq (carbon credit)[2]	Production cost	Biochar yield	Retention time	Crop productivity impact
	t CO_2 eq/t	% C	EUR/t CO_2 eq	EUR/t biochar	% of dry mass	Relative index (1–3)	% yield gain
HP-W	2.51	90 % [32]	369.38	1000 [22]	15 % [33], [34], [45]	2 [35], [36]	5 % [37], [38]
HP-H	2.12	69 % [32]	311.81	1003 [21]	28 % [37], [38], [41], [45]	2 [27], [35], [36]	5 % [38]
HP-B	1.14	29 % [32], [42]	167.90	878 [43]	20 % [39], [44], [45]	2 [36]	10 % [46]
MP-W	2.26	88 % [47]	332.02	970 [22]	30 % [34], [48]	3 [35], [36]	10 % [31], [38]
MP-H	1.91	68 % [32], [47]	280.28	970 [22]	32 % [40], [41], [48]	3 [27], [35], [36]	15 % [37], [49]
MP-B	1.03	29 % [32], [42]	150.92	790 [43]	25 % [50], [51]	3 [36], [52]	30 % [53], [54]
LP-W	1.84	75 % [47]	269.77	676 [43], [55]	35 % [33], [34], [39	3 [35], [36]	20 % [56]
LP-H	1.55	60 % [47]	227.73	203 [57], [58]	48 % [39], [40], [59]	3 [35], [36], [52]	25 % [37]
LP-B	0.83	35 % [42]	122.62	614 [43]	35 % [51], [52]	3 [36], [52]	30 % [53], [54]
G-W	1.70	67 % [29]	249.45	280 [60]	10 % [33], [34]	1 [36], [52], [61], [62]	11 % [38]
G-H	0.91	59 % [29]	134.32	280 [60]	10 % [29], [63]	1 [36], [52], [62], [64]	11 % [38]
G-B	0.23	33 % [65]	33.58	280 [60]	24 % [66]	1 [36], [52], [62]	10 % [38], [46]

[1] value was calculated based on TIER 1 IPCC methodology
[2] value was calculated based on sequestrated carbon multiplying with Carbon Removal Price Index
[3] values from HP-B scenario

Two indicators were selected for the economic indicator category: profit per ton CO_2 eq. (carbon credit) (EUR/t CO_2 eq.) and production cost (EUR/ t biochar). Production cost of biochar was selected because it directly impacts the market competitiveness of biochar. Higher production costs can limit the ability of biochar producers to achieve economies of scale, compete in agricultural and carbon markets, thus limiting the large-scale uptake of biochar as a climate mitigation tool [21]. Production cost data were retrieved from peer-reviewed scientifical articles, in cases where production cost data were not available, minimum selling price (MSP) values for final biochar product were used. This assumption was made, because MSP reflects the breakeven price required to cover both capital and operating costs under realistic market conditions [22]. All values were converted to EUR value in 2025 to maintain consistency. Profit from carbon credits obtained for one tonne of biochar produced from different feedstock and technology mix was calculated multiplying carbon sequestration potential from one tonne of biochar amended to soil (tCO_2eq/t) with CORC (Carbon Removal Price Index CORCCHAR), which in April of 2025 was 133.84 EUR/t CO_2eq [23].

Two technological category indicators were selected: biochar yield (%) and retention time (minutes). Biochar yield is expressed as % of mass of initial feedstock converted to biochar and is considered one of the most critical biochar production technology performance indicators, this indicator is closely linked with economic feasibility, as it affects the amount which can be sold per unit of feedstock [24], [25]. Biochar yield can significantly vary depending on feedstock and technology usage [26]. Data for biochar yield were retrieved from peer-reviewed scientific articles reporting experimentally measured yield values for different feedstock and technologies. Retention time was selected as a technical indicator, because it affects biochar quality and process efficiency, longer retention time leads to higher energy input, but more stable biochar, while shorter retention time allows to have faster production [27]–[29]. As there is big variability in retention time between different combination of biochar production technologies and feedstocks, in this case study used index-based evaluation. Three level index scale was used to represent the relative differences between scenarios. Technologies with lowest retention time were assigned a value of 1, with highest retention time – value of 3. This approach allowed to compare diverse technological configurations, which in this case are context dependent [14]. Index based approach is used when quantitative data are uncertain or not directly comparable, this method allows to reflect which alternative is better than other [30].

For the agronomic indicator category one indicator – crop productivity impact (% crop yield gain) – was selected. This indicator was chosen because it shows relative changes in crop productivity, if biochar is amended in soil [31]. All values for this study were taken from peer reviewed studies. Due to limited availability of data on crop productivity impacts of gasification derived biochar, yield change values for these scenarios were estimated using pyrolysis derived data from the same temperature regime. It is acknowledged that gasification biochar exhibits different physicochemical properties, which may affect crop productivity. This limitation is recognized as a research gap in this study.

2.2. Multi – Criteria Decision Analysis with TOPSIS

TOPSIS was selected due to its effectiveness in sustainability assessments and multi-criteria decision making [67]. TOPSIS enables to rank alternatives based on their proximity (shortest Euclidean distance) to an ideal solution that maximizes benefits and minimizes costs [68]. In this study indicators include both benefit and cost type.

TOPSIS method can be described in 6 steps [69]:

1. Normalizing the decision matrix – to compare different indicators, they need to be dimensionless. This is done using fallowing equation:

$$r_{kj}\left(x\right)=\frac{x_{kj}}{\sum_{k=1}^{n}x_{kj}^{2}},k=1,\ldots,n;\ j=1,\ldots,m \quad (1)$$

2. Calculating the normalized weighted matrix, where each normalized value is multiplied by assigned weight:

$$V = \left(v_{kj}\right)_{n \times m} \tag{2}$$

$$v_{kj} = w_j \times r_{kj}, \tag{3}$$

where w_j represents assigned weight to j indicator.

3. Determination of the best (V^{+}) and worst (V^{-}) ideal:

$$V^{+} = \left\{v_1^{+}, v_{2,}^{+} v_3^{+}, \ldots, v_n^{+}\right\} = \left\{\left(\max_k v_{kj} \mid j \in J_1\right), \left(\min_k v_{kj} \mid j \in J_2\right) \mid k = 1, \ldots, n\right\} \tag{4}$$

and

$$V^{-} = \left\{v_1^{-}, v_{2,}^{-} v_3^{-}, \ldots, v_n^{-}\right\} = \left\{\left(\min_k v_{kj} \mid j \in J_1\right), \left(\max_k v_{kj} \mid j \in J_2\right) \mid k = 1, \ldots, n\right\}, \tag{5}$$

where J_1 and J_2 represents benefit and cost type criteria.

4. Calculation of the distance from best and worst ideal using Euclidean distance:

$$D_k^{+} = \sqrt{\sum_{j=1}^{m} \left[v_{kj} - v_j^{+}\right]^2}, k = 1, \ldots, n \tag{6}$$

and

$$D_k^{-} = \sqrt{\sum_{j=1}^{m} \left[v_{kj} - v_j^{-}\right]^2}, k = 1, \ldots, n \tag{7}$$

5. Calculation of relative closeness (C_i) to the ideal value:

$$C_i = \frac{D_k^{-}}{D_k^{+} + D_k^{-}}, k = 1, \ldots, n, \tag{8}$$

where C_i range should be between 0 and 1.

6. Ranking of scenarios – the scenarios are ranked from best to worst value. Best value is with highest C_i score.

2.3. Sensitivity Analysis

To assess the robustness and stability of the scenario ranking under varying stakeholder priorities a sensitivity analysis was conducted. This involved systematically adjusting the weight of each sustainability dimension – environmental, economic, technological, agronomic, ranging from 0.01 to 3 (equivalent to 0.25 % to 75 % of total weight). In each simulation, the remaining weight was equally distributed among other dimensions. This approach allowed to simulate shift in decision-making priorities, such as increased emphasis on environmental performance over economic or vice versa. By observing changes in scenario ranking under these conditions the analysis provided insight into the resilience of the recommended options and the influence of individual criteria on the outcome.

3. Results and Discussion

3.1. Baseline TOPSIS Results

In baseline scenario the TOPSIS method was used to assess and rank 12 biochar production scenarios based on four sustainability categories: environmental, economic, technological, agronomic. Each category was assigned an equal weight of 25 %. Environmental, economic and technological categories had two indicators each, and the weight was evenly distributed between the indicators in these categories. As a result, closeness scores (C_i) for each scenario where calculated, therefore allowing to range these scenarios (see Fig. 1). Higher values of Ci represent better performance across selected data.

As can be seen from Fig. 1, the highest score was reached by low-temperature pyrolysis using herbaceous feedstock (LP – H) with a score 0.69. Comparing to other technology – feedstock mixes LP-H had high biochar yield and good impact on crop yield, as well, it had low production costs. The second and third best alternatives were, accordingly, MP-B and LP-B, despite that biochar produced with these scenarios had lower carbon content, it had high yield and good impact on crop productivity. Biosolids contains significant amount of both organic and inorganic nutrient, a portion of which is retained in the resulting biochar following pyrolysis process. Nutrients such as phosphorus, magnesium, potassium, can enrich soil improving its fertility and promoting plant growth [54]. Biosolids and herbaceous feedstocks often are available either free of on very low cost, and in some cases, producers are paid or subsidized to take them due to disposal requirements, thus reducing production cost [70].

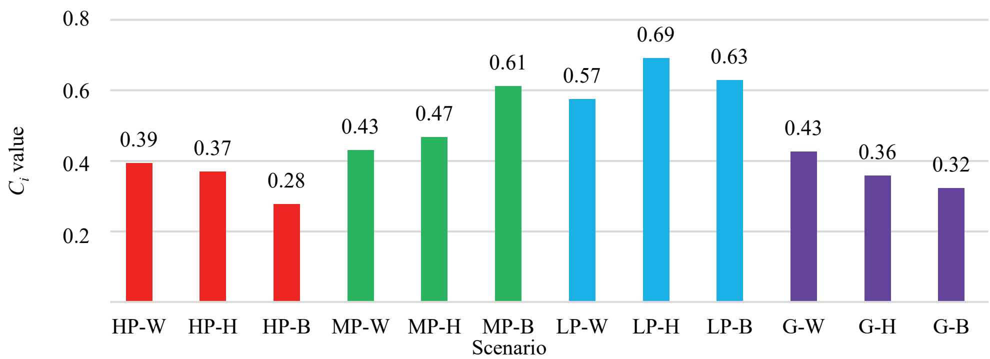

Fig. 1. TOPSIS Closeness Coefficient (C_i) by Scenario.

Contrary, HP-B and G-B alternatives were evaluated with the lowest scores, that can be explained by low carbon sequestration potential. According to IPCC methodology, a 1 ton of biochar from biosolids, when amended in soil, sequestrates the lowest amount of carbon in comparison to alternatives, as well due to high temperatures, biochar tends to have lower impacts on the crop yield comparing to biochar yielded with lower temperature [17]. As well HP-B scenario, according to research [39], [44], [45] and G-B, according to research [66], have lower biochar yield, then other scenarios with different feedstock. It should be noted that primary aim of gasification process is syngas production, thus maximizing gas yield over solid residue yield, thus biochar becoming by-product. As well, biochar which is produced through gasification is having lower surface area and pore size, compared to slow pyrolysis, due to ash melting and pore clogging. This factor limits biochar produced with gasification as soil amendment technology, because biochar with higher surface area tends to improve soil characteristics: boost water retention, soil aeration, nutrient exchange and remove pollutants from soil [66].

HP-W and HP-H have lower ranking due to higher production costs per one ton produced biochar and reduced positive effect on crop yield, this can be explained by fact that when biomass is exposed to high temperature, more nutrients are lost in production process than at lower temperatures [71]. Wood biomass compared to herbaceous and biosolids is considered more expensive feedstock. As well technologies which includes higher temperature regimes requires higher energy demand thus increasing production costs [14].

3.2. Sensitivity Analysis Results

To evaluate robustness of TOPSIS baseline ranking and assess how ranking changes under shifting a Sensitivity analysis was performed. Four separate weighting scenarios were tested, each simulated a decision-making context for particular dimension (environmental, economic, technological, agronomic) with different priority weights (from 0.25 % to 75 %).

Fig. 2 shows changes in TOPSIS rankings for 12 scenarios considering different weight for environmental indicator. LP-H scenario maintains overall highest score, showing overall balance even when priorities are shifting. When environmental category indicators are assigned lowest weight from all categories, low and medium temperature pyrolysis have best score, while high temperature pyrolysis and gasification have lowest score. With increasing weight to environmental indicators all technological processes with woody feedstock improve their score, this can be explained by sequestrated carbon potential (according to IPCC methodology highest sequestrated carbon amount accrue from biochar produced from woody biomass feedstock), as well such biochar tends to contain higher percentage of carbon content [17], [32]. After base line point (for each category weight is 25 %) scenarios utilizing biosolids as feedstock starts to show gradual decline in score, due to lower carbon content % and reduced carbon sequestration. Carbon content in biochar produced from biosolids tend to be lower, because biosolid such as a sewage sludge contains lower amount of cellulose, hemicellulose, lignin etc., opposite to herbaceous or woody biomass [72]. Gasification scenarios, particularly G-B, remained among the lowest-performing throughout, reflecting lower environmental efficiency, however it is important to note the results are derived with specific set of indicators selected for study.

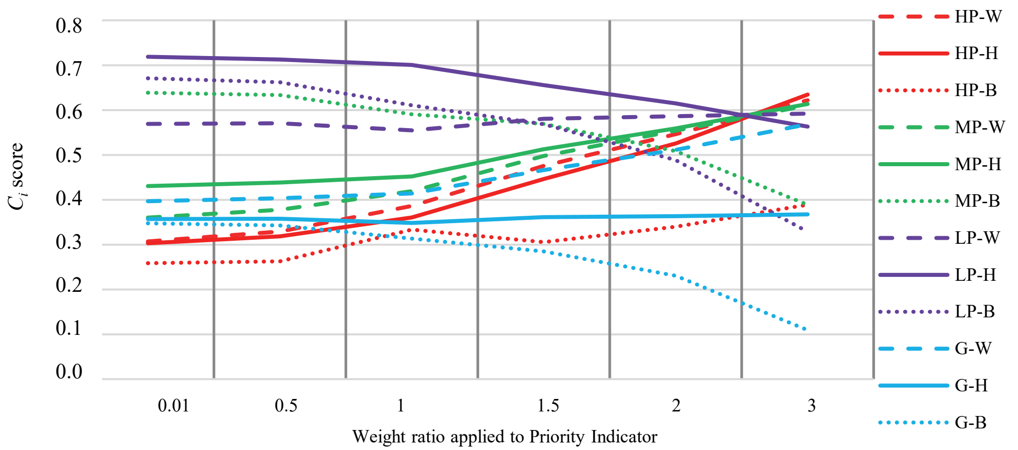

Fig. 2. TOPSIS closeness coefficients (C_i) for biochar technology – feedstock combinations under the environmental priority scenario.

When the weight of economic indicators was changed, a distinct shift in ranging emerged (Fig. 3). Gasification with herbaceous and woody biomass improved their score with increasing weight in economic indicators, these changes occurred due to lower estimated production costs. G-W scenario score increased two times, showing strong connection between low production costs and overall ranking, at the end making it as one of the top scenarios (along LP-H). In contrast scenarios which had good score previously (MP-H) had decline in score when bigger weight is assigned to economic indicators due to assumed higher production cost.

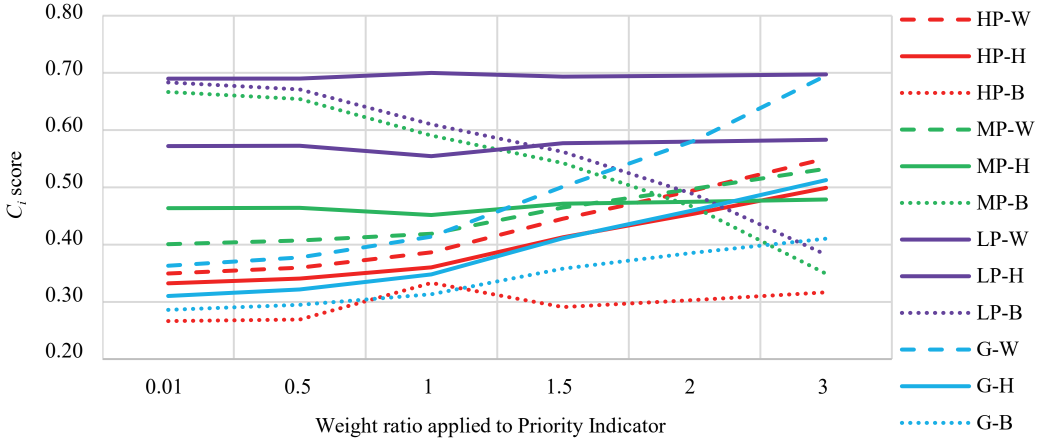

Fig. 3. TOPSIS closeness coefficients (C_i) for biochar technology – feedstock combinations under the economic priority scenario.

The results of sensitivity analysis for technology indicators are presented in Fig. 4. Best results were achieved for LP-H scenario, with slight decrease after baseline scenario, but maintaining leader position under shifting priorities. Scenarios with higher biochar yield obtained best results with increased weight of technology indicator. Notably, HP-B scenario score increased from 0.27 to 0.52 (at 75 % weight), thus making this scenario reach one of the highest scores in this case.

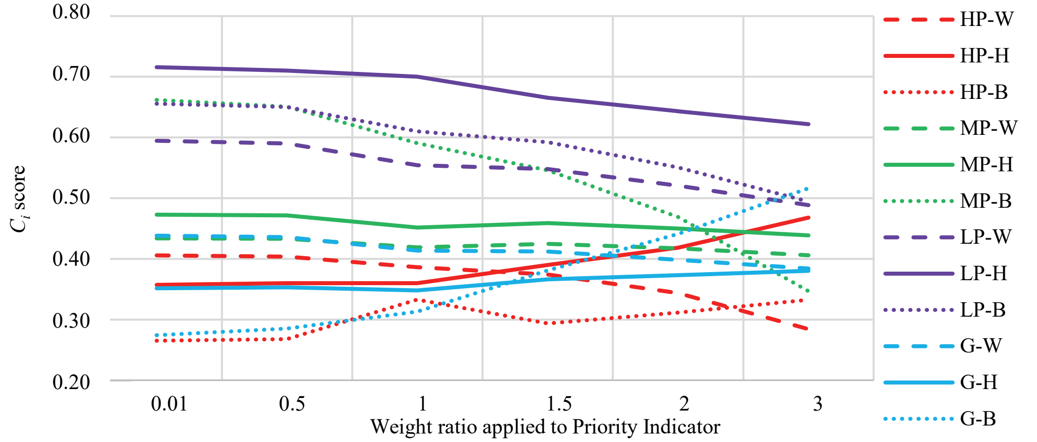

Fig. 4. TOPSIS closeness coefficients (C_i) for biochar technology – feedstock combinations under the technological priority scenario.

All the higher temperature scenarios reached lower score with increasing priority for technological indicators. This is because, due to increase of thermal decomposition and devolatilization of the biomass, when biochar is produced at higher temperatures, biochar yield is lower than at lower temperatures. Higher temperature tends to increase proportion of volatile compounds and bio-oils and reducing solid residue proportion. Additionally higher temperatures promote structural changes such as pore collapse or clogging, further reducing yield [73]. When weight of the agronomic category was changed, scenarios utilizing biosolids as feedstock had significant score increase, reaching overall highest score (at 75 %) 0.93 MP-B and 0.83 LP-B scenarios.

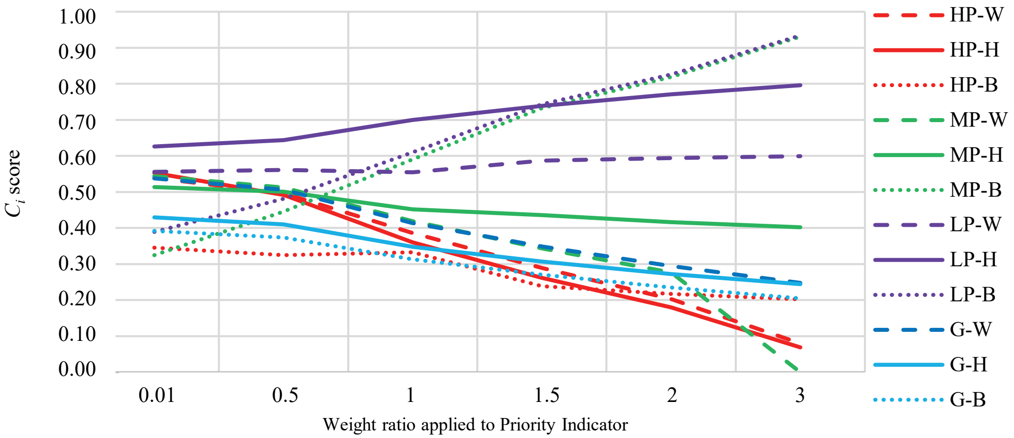

Fig. 5. TOPSIS closeness coefficients (C_i) for biochar technology - feedstock combinations under the agronomic priority scenario.

These changes reflect high crop productivity attributed to biosolids derived biochar. However, it should be noted that while biosolids derived biochar can boost crop productivity, it may also carry environmental and regulatory concerns due to potential presence of heavy metals and organic contaminants, this may have negative effect on production cost and yield, therefore additional treatment to remove heavy metal must be introduced [54]. A study [74] suggests using higher temperatures to get rid of heavy metals in biochar, but that could potentially lower biochar yield and quality. Due to lower impact on crop productivity, scenarios with woody biomass tend to have lower rank than scenarios which use herbaceous or biosolids as feedstock. This decrease can be explained by the lower nutrient retention rate, which is typical for wood derived biochar [75], on the other hand, it has high lignin and cellulose content. As well it can be seen that technologies with higher temperatures regimes (pyrolysis or gasification) are getting lower score as bigger weight is assigned to crop productivity.

4. Conclusion

The baseline scenario revealed that low and medium temperature pyrolysis with herbaceous and biosolids feedstock outperformed other combinations. These combinations ranked higher due to favourable production costs, higher biochar yields and improved agronomic output – such as crop productivity enhancement. Low temperature pyrolysis with herbaceous feedstock consistently achieved highest score, highlighting this technology/feedstock combination as most suitable evaluated combination, even when decision making priorities are shifting, emphasizing environmental, economic, agronomic or technological dimension.

The study showed that the feedstock type and temperature regime play crucial role in determining economic, environmental, agronomic performance. Sensitivity analysis emphasizes the impact of decision-making priorities on scenario ranking. When environmental or agronomic category was prioritized, it significantly altered the weight, underscoring the context dependence of optimal solution. For example, gasification scenarios consistently gained lower score under most priority settings, indicating limited suitability for biochar focused application where agronomic and environmental (carbon sequestration) goals are dominating. These shifts confirm that the performance and selection of biochar production pathways are highly sensitive to decision making priorities and underscore the relevance of indicator selection and data availability. Future study should include additional indicators, like biochar surface area and market price, to better evaluate technical performance of biochar and economical profit of biochar production. As well, focus on the field scale validation of model scenarios must be done, including life cycle assessment for comprehensive impact assessment and explore co-processing strategies to optimize trade-offs between carbon stability and nutrient availability.

ACKNOWLEDGEMENT

This research is funded by The National Research Program of the Latvian Science Council "Decision-making Support System for Achieving Climate Neutrality Goals" Project no. VPP-KEM-Klimatneitralitāte-2023/1-0002. Contract/reg no. 0B000-3.1.2.1-e/49.

REFERENCES

[1] Communication from the commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. Brussels, 2019.

[2] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). *Official Journal of the European Union* 2021 L 243/1.

[3] Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU (Text with EEA relevance) Text with EEA relevance. 2023.

[4] Klimata un enerģētikas ministrija. Nacionālais enerģētikas un klimata plāns 2021.–2030. gadam (Ministry of Climate and Energy. National Energy and Climate Plan 2021–2030). [Online]. [Accessed 04.11.2024]. Available: https://www.kem.gov.lv/lv/nacionalais-energetikas-un-klimata-plans-2021-2030-gadam (In Latvian).

[5] Latvia`s National Inventory Report under the UNFCCC Greenhouse Gas Emissions in Latvia from 1990 to 2022. 2024. [Online]. [Accessed 04.11.2024]. Available: https://unfccc.int/ghg-inventories-annex-i-parties/2024

[6] Brad A., Schneider E. Carbon dioxide removal and mitigation deterrence in EU climate policy: Towards a research approach. *Environmental Science & Policy* 2023:150:103591. https://doi.org/10.1016/j.envsci.2023.103591

[7] European Parliament. Carbon dioxide removal: Nature-based and technological solutions. 2021. [Online]. [Accessed 04.11.2024]. Available: https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2021)689336

[8] IATA. Carbon Dioxide Removal (CDR) Technologies An overview of the different methods for capturing and storing carbon dioxide from the atmosphere. 2025. [Online]. [Accessed 12.06.2025]. Available: https://www.iata.org/globalassets/iata/publications/sustainability/carbon-dioxide-removal-cdr-technologies-facts.pdf

[9] Vaccari F. P., *et al*. Biochar as a strategy to sequester carbon and increase yield in durum wheat. *European Journal of Agronomy* 2011:34(4):231–238. https://doi.org/10.1016/j.eja.2011.01.006

[10] He D., Luo Y., Zhu B. Feedstock and pyrolysis temperature influence biochar properties and its interactions with soil substances: Insights from a DFT calculation. *Science of the Total Environment* 2024:922:171259. https://doi.org/10.1016/j.scitotenv.2024.171259

[11] Gao Y. *et al*. Influences of soil and biochar properties and amount of biochar and fertilizer on the performance of biochar in improving plant photosynthetic rate: A meta-analysis. *European Journal of Agronomy* 2021:130:126345. https://doi.org/10.1016/j.eja.2021.126345

[12] Amalina F., Razak A. S. A., Krishnan S., Sulaiman H., Zularisam A. W., Nasrullah M. Biochar production techniques utilizing biomass waste-derived materials and environmental applications – A review. *Journal of Hazardous Materials Advances* 2022:7:100134. https://doi.org/10.1016/j.hazadv.2022.100134

[13] Chen J. *et al*. A complete review on the oxygen-containing functional groups of biochar: Formation mechanisms, detection methods, engineering, and applications. *Science of the Total Environment* 2024:946:174081. https://doi.org/10.1016/j.scitotenv.2024.174081

[14] Tomczyk A., Sokołowska Z., Boguta P. Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology* 2020:19(1):191–215. https://doi.org/10.1007/s11157-020-09523-3

[15] Rajput V. *et al*. Biochar production methods and their transformative potential for environmental remediation. *Discover Applied Science* 2024:6(8):408. https://doi.org/10.1007/s42452-024-06125-4

[16] Lefebvre D., Fawzy S., Aquije C., Osman A. I., Draper K., Trabold T. A. Biomass residue to carbon dioxide removal: quantifying the global impact of biochar. *Biochar* 2023:5:65. https://doi.org/10.1007/s42773-023-00258-2

[17] C. B. E et al., IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, vol. 4. Intergovernmental Panel on Climate Change, 2019. [Online]. [Accessed 04.11.2024]. Available: https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Generic%20Methods.pdf

[18] Waheed A. *et al*. Biochar in sustainable agriculture and Climate Mitigation: Mechanisms, challenges, and applications in the circular bioeconomy. *Biomass Bioenergy* 2025:193:107531. https://doi.org/10.1016/j.biombioe.2024.107531

[19] Wang L., Chen D., Zhu L. Biochar carbon sequestration potential rectification in soils: Synthesis effects of biochar on soil CO_2, CH_4 and N_2O emissions. *Science of the Total Environment* 2023:904:167047. https://doi.org/10.1016/j.scitotenv.2023.167047

[20] Li S., Tasnady D. Biochar for Soil Carbon Sequestration: Current Knowledge, Mechanisms, and Future Perspective. *Journal of Carbon Research* 2023:9(3):67. https://doi.org/10.3390/c9030067

[21] Nematian M., Keske C., Ng'ombe J. N. A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. *Waste Management* 2021:135:467–477. https://doi.org/10.1016/j.wasman.2021.09.014

[22] Sahoo K., Bilek E., Bergman R., Mani S. Techno-economic analysis of producing solid biofuels and biochar from forest residues using portable systems. *Applied Energy* 2019:235:578–590. https://doi.org/10.1016/j.apenergy.2018.10.076

[23] CORC Biochar Price Index CORCCHAR. [Online]. [Accessed 02.05.2025]. Available: https://puro.earth/corc-carbon-removal-indexes

[24] Campion L., Bekchanova M., Malina R., Kuppens T. The costs and benefits of biochar production and use: A systematic review. *Journal of Cleaner Production* 2023:408:137138. https://doi.org/10.1016/j.jclepro.2023.137138

[25] Bach M., Wilske B., Breuer L. Current economic obstacles to biochar use in agriculture and climate change mitigation. *Carbon Management* 2016:7:3–4. https://doi.org/10.1080/17583004.2016.1213608

[26] Safarian S. Performance analysis of sustainable technologies for biochar production: A comprehensive review. *Energy Reports* 2023:9:4574–4593. https://doi.org/10.1016/j.egyr.2023.03.111

[27] Wystalska K., Malińska K., Włodarczyk R., Chajczyk O. Effects of pyrolysis parameters on the yield and properties of biochar from pelletized sunflower husk. *E3S Web of Conferences* 2018:44:00197. https://doi.org/10.1051/e3sconf/20184400197

[28] K. K. V and N. L. Panwar, Pyrolysis technologies for biochar production in waste management: a review. *Clean Energy* 2024:8(4):61–78. https://doi.org/10.1093/ce/zkae036

[29] Fryda L., Visser R. Biochar for Soil Improvement: Evaluation of Biochar from Gasification and Slow Pyrolysis. *Agriculture* 2015:5(4):1076–1115. https://doi.org/10.3390/agriculture5041076

[30] Cinelli M., Coles S. R., Kirwan K. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators* 2014:46:138–148. https://doi.org/10.1016/j.ecolind.2014.06.011

[31] Jiang Y., Li T., Xu X., Sun J., Pan G., Cheng K. A global assessment of the long-term effects of biochar application on crop yield. *Current Research in Environmental Sustainability* 2024:7:100247. https://doi.org/10.1016/j.crsust.2024.100247

[32] Li Q., Zhang X., Mao M., Wang X., Shang J. Carbon content determines the aggregation of biochar colloids from various feedstocks. *Science of the Total Environment* 2023:880:163313. https://doi.org/10.1016/j.scitotenv.2023.163313

[33] Amonette J. E. *et al*. Biomass to biochar: Maximizing the carbon value.

[34] Lehmann J., Joseph S., Eds., Biochar for environmental management: science and technology. London; Sterling, VA: Earthscan, 2009.

[35] Sun J., He F., Pan Y., Zhang Z. Effects of pyrolysis temperature and residence time on physicochemical properties of different biochar types. *Acta Agriculturae Scandinavica, Section B – Soil and Plant Science* 2017:67(1):12–22. https://doi.org/10.1080/09064710.2016.1214745

[36] Ganesapillai M. *et al*. Waste to energy: A review of biochar production with emphasis on mathematical modelling and its applications. *Heliyon* 2023:9(4):e14873. https://doi.org/10.1016/j.heliyon.2023.e14873
[37] Ye L., Camps-Arbestain M., Shen Q., Lehmann J., Singh B., Sabir M. Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use and Management* 2020:36(1):2–18. https://doi.org/10.1111/sum.12546
[38] Subedi R., Bertora C., Zavattaro L., Grignani C. Crop Response to Soils Amended with Biochar: Expected Benefits and Unintended Risks. *Ital. J. Agron*. 2017:12(2):794. https://doi.org/10.4081/ija.2017.794
[39] Chun Y., Lee S. K., Yoo H. Y., Kim S. W. Recent advancements in biochar production according to feedstock classification, pyrolysis conditions, and applications: A review. *BioResources* 2021:16(3):6512–6547. https://doi.org/10.15376/biores.16.3.Chun
[40] Naeem M. A., Khalid M., Arshad M., Ahmad R. Yield and Nutrient Composition of Biochar Produced from Different Feedstocks at Varying Pyrolytic Temperatures.
[41] Sedmihradská A. *et al*. Pyrolysis of wheat and barley straw. *Research in Agricultural Engineering* 2020:66(1):8–17. https://doi.org/10.17221/26/2019-RAE
[42] Seow Y. X. *et al*. A review on biochar production from different biomass wastes by recent carbonization technologies and its sustainable applications. *Journal of Environmental Chemical Engineering* 2022:10(1):107017. https://doi.org/10.1016/j.jece.2021.107017
[43] Zhang P., Duan W., Peng H., Pan B., Xing B. Functional Biochar and Its Balanced Design. *ACS Environmental Au* 2022:2(2):115–127. https://doi.org/10.1021/acsenvironau.1c00032
[44] Khanmohammadi Z., Afyuni M., Mosaddeghi M. R. Effect of pyrolysis temperature on chemical and physical properties of sewage sludge biochar. *Waste Management & Research: The Journal of Sustainable Circular Economy* 2015:33(3):275–283. https://doi.org/10.1177/0734242X14565210
[45] Agrafioti E., Bouras G., Kalderis D., Diamadopoulos E. Biochar production by sewage sludge pyrolysis. *Journal of Analytical and Applied Pyrolysis* 2013:101:72–78. https://doi.org/10.1016/j.jaap.2013.02.010
[46] Zhao L. *et al*. Sewage sludge derived biochar for environmental improvement: Advances, challenges, and solutions. *Water Research X* 2023:18:100167. https://doi.org/10.1016/j.wroa.2023.100167
[47] Kuryntseva P., Karamova K., Galitskaya P., Selivanovskaya S., Evtugyn G. Biochar Functions in Soil Depending on Feedstock and Pyrolyzation Properties with Particular Emphasis on Biological Properties. *Agriculture* 2023:13(10). https://doi.org/10.3390/agriculture13102003
[48] Al-Rumaihi A., Shahbaz M., Mckay G., Mackey H., Al-Ansari T. A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. *Renewable and Sustainable Energy Reviews* 2022:167:112715. https://doi.org/10.1016/j.rser.2022.112715
[49] Zhang L. *et al*. Meta-Analysis of the Response of the Productivity of Different Crops to Parameters and Processes in Soil Nitrogen Cycle under Biochar Addition. *Agronomy* 2022:12(8):1857. https://doi.org/10.3390/agronomy12081857
[50] Kumar V. K., Panwar N. L. Pyrolysis technologies for biochar production in waste management: a review. *Clean Energy* 2024:8(4):61–78. https://doi.org/10.1093/ce/zkae036
[51] Suresh Babu K. K. B., Nataraj M., Tayappa M., Vyas Y., Mishra R. K., Acharya B. Production of biochar from waste biomass using slow pyrolysis: Studies of the effect of pyrolysis temperature and holding time on biochar yield and properties. *Material Science for Energy Technology* 2024:7:318–334. https://doi.org/10.1016/j.mset.2024.05.002
[52] Sharma S. *et al*. Biochar as a Potential Nutrient Carrier for Agricultural Applications. *Current Pollution Reports* 2025:11(1):19. https://doi.org/10.1007/s40726-025-00349-7
[53] Jeffery S., Verheijen F. G. A., Van Der Velde M., Bastos A. C. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture Ecosystems and Environment* 2011:144(1):175–187. https://doi.org/10.1016/j.agee.2011.08.015
[54] Mcintyre H., Li S. From Waste to Resource: Evaluating the Impact of Biosolid-Derived Biochar on Agriculture and the Environment. *Biomass* 2024:4(3):809–825. https://doi.org/10.3390/biomass4030045
[55] Keske C., Godfrey T., Hoag D. L. K., Abedin J. Economic feasibility of biochar and agriculture coproduction from Canadian black spruce forest. *Food and Energy Security* 2020:9(1):e188. https://doi.org/10.1002/fes3.188
[56] Han M., Zhang J., Zhang L., Wang Z. Effect of biochar addition on crop yield, water and nitrogen use efficiency: A meta-analysis. *Journal of Cleaner Production* 2023:420:138425. https://doi.org/10.1016/j.jclepro.2023.138425
[57] Patel M. R., Panwar N. L. Evaluating the agronomic and economic viability of biochar in sustainable crop production. *Biomass Bioenergy* 2024:188:107328. https://doi.org/10.1016/j.biombioe.2024.107328
[58] Li S., Chen G. Thermogravimetric, thermochemical, and infrared spectral characterization of feedstocks and biochar derived at different pyrolysis temperatures. *Waste Management* 2018:78:198–207. https://doi.org/10.1016/j.wasman.2018.05.048
[59] Javaid S. F. *et al*. Production of Biochar by Slow and Solar-Biomass Pyrolysis: Focus on the Output Configuration Assessment, Adaptability, and Barriers to Market Penetration. *Arabian Journal for Science and Engineering* 2024:49(6):7731–7750. https://doi.org/10.1007/s13369-023-08549-3

[60] Guerrero J., Sala S., Fresneda-Cruz A., Bolea I., Carmona-Martínez A. A., Jarauta-Córdoba C. Techno-Economic Feasibility of Biomass Gasification for the Decarbonisation of Energy-Intensive Industries. *Energies* 2023:16(17):6271. https://doi.org/10.3390/en16176271

[61] Andrew R., Gokak D. T., Sharma P., Sharma J., Somkuwar N., Gupta S. Practical Achievements on Biomass Steam Gasification in a Rotary Tubular Coiled-downdraft Reactor. *Procedia Environmental Sciences* 2016:35:818–825. https://doi.org/10.1016/j.proenv.2016.07.098

[62] Kumari K., Kumar R., Bordoloi N., Minkina T., Keswani C., Bauddh K. Unravelling the Recent Developments in the Production Technology and Efficient Applications of Biochar for Agro-Ecosystems. *Agriculture* 2023:13(3):512. https://doi.org/10.3390/agriculture13030512

[63] Safarian S. Performance analysis of sustainable technologies for biochar production: A comprehensive review. *Energy Reports* 2023:9:4574–4593. https://doi.org/10.1016/j.egyr.2023.03.111

[64] Wang L., Zhou T., Hou B., Yang H., Hu N., Zhang M. A Comprehensive Review of Biomass Gasification Characteristics in Fluidized Bed Reactors: Progress, Challenges, and Future Directions. *Fluids* 2025:10(6):147. https://doi.org/10.3390/fluids10060147

[65] Pulka J., Wiśniewski D., Gołaszewski J., Białowiec A. Is the biochar produced from sewage sludge a good quality solid fuel? *Archives of Environmental Protection* 2016:42(4):125–134. https://doi.org/10.1515/aep-2016-0043

[66] You S. *et al*. A critical review on sustainable biochar system through gasification: Energy and environmental applications. *Bioresource Technology* 2017:246:242–253. https://doi.org/10.1016/j.biortech.2017.06.177

[67] Madanchian M., Taherdoost H. A comprehensive guide to the TOPSIS method for multi-criteria decision making. *Sustainable Social Development* 2023:1(1). https://doi.org/10.54517/ssd.v1i1.2220

[68] Tzeng G.-H., Huang J.-J. Multiple Attribute Decision Making: Methods and Applications.

[69] Safronova A., Barisa A., Kirsanovs V. Linking Sustainable Mobility Criteria to Policymaking: Results of Multi-Criteria Analysis. *EAI Endorsed Trans. Energy Web* 2022:9(39):e7. https://doi.org/10.4108/ew.v9i39.1549

[70] Ahmed S. F. *et al*. Biochar produced from waste-based feedstocks: Mechanisms, affecting factors, economy, utilization, challenges, and prospects. *GCB Bioenergy* 2024:16(8):e13175. https://doi.org/10.1111/gcbb.13175

[71] Rajkovich S., Enders A., Hanley K., Hyland C., Zimmerman A. R., Lehmann J. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Biology and Fertility of Soils* 2012:48(3):271–284. https://doi.org/10.1007/s00374-011-0624-7

[72] Cao J. *et al*. Sludge-based biochar preparation: pyrolysis and co-pyrolysis methods, improvements, and environmental applications. *Fuel* 2024:373:132265. https://doi.org/10.1016/j.fuel.2024.132265

[73] Elnour A. Y. *et al*. Effect of Pyrolysis Temperature on Biochar Microstructural Evolution, Physicochemical Characteristics, and Its Influence on Biochar/Polypropylene Composites. *Applied Science* 2019:9(6):1149. https://doi.org/10.3390/app9061149

[74] Elkhalifa S., Mackey H. R., Al-Ansari T., McKay G. Pyrolysis of Biosolids to Produce Biochars: A Review. *Sustainability* 2022:14(15):9626. https://doi.org/10.3390/su14159626

[75] Domingues R. R. *et al*. Properties of biochar derived from wood and high-nutrient biomasses with the aim of agronomic and environmental benefits. *PLOS ONE* 2017:12(5):1–19. https://doi.org/10.1371/journal.pone.0176884