



Research Article

# A Fuzzy Multi-Criteria Approach for Assessing Regional Biochar Market Potential

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**Abstract:** The agricultural sector in the Russian Federation generates substantial volumes of organic waste, creating significant environmental challenges and presenting an opportunity for value-added products such as biochar. While biochar offers proven benefits for soil improvement, carbon sequestration, and waste valorization, no systematic, nationwide assessment of its market potential exists. This study aims to develop and apply a structured, multi-criteria approach to evaluate and rank the biochar sales potential of Russian regions. A fuzzy multiple-criteria decision-making model was constructed using six proxy indicators linked to key biochar applications: mineral fertilizer application rate (X1), fresh water usage for irrigation (X2), area of degraded land (X3), feed consumption per conventional head of cattle (X4), cattle population (X5), and sales volume of main agricultural products (X6). Weights were assigned based on each application's scale and quality requirements. The model was applied to statistical data from 78 Russian regions, and K-means and hierarchical clustering analysis were used to validate the results. The primary outcome of this study is the development of a replicable fuzzy multi-criteria approach for assessing the market potential of biochar. The application of the approach is demonstrated through the first comprehensive ranking of Russian regions by biochar sales potential. The Krasnodar Territory was identified as having the highest potential (indicator value = 0.186), followed by the Rostov Oblast (0.320) and the Saratov Oblast (0.335). In total, 15 regions were classified as having "High" or "Very High" potential, whereas more than 20 fell into the "Medium" category. Cluster analysis validated these rankings and revealed three distinct regional profiles based on their underlying socio-agro-economic characteristics. This study provides a novel, data-driven spatial framework for assessing the potential of the biochar market at a national scale. The resulting regional ranking offers a foundational tool for informing strategic decisions on the siting of biochar production facilities and for designing targeted, region-specific market development policies for Russia's emerging biochar economy.

**Keywords:** Biochar; Biochar market; Cluster analysis; Fuzzy logic; Regional assessment

## 1. Introduction

Russia's highly developed agricultural sector generates substantial organic waste from various activities. However, this waste stream's potential as a raw material for production remains largely unrealized (Trippe and Phillips, 2018). The term "biochar" is relatively recent. The International Biochar Initiative defines biochar as a solid material obtained from the pyrolysis of biomass in an oxygen-limited environment at temperatures below 700 °C (Bhattacharya et al., 2024). Biochar is a subject of active discussion in agriculture, particularly regarding its role in recycling organic waste and improving soil properties (Lin et al., 2025). Beyond soil enhancement, biochar contributes to carbon sequestration, preventing carbon release into the atmosphere and offering a promising natural carbon capture solution (Cheng et al., 2025). Converting agricultural waste into biochar provides a valuable soil additive and provides an alternative to residue burning for farmers. This additive can improve soil quality, reduce wa-

ter consumption, lower methane emissions, and reduce the reliance on expensive and polluting chemical fertilizers (Campion et al., 2023; International Biochar Initiative, 2015). Research on substituting a portion of fertilizers with biochar confirms its significant potential. For instance, a long-term experiment by Wu et al., 2024 demonstrated increased soybean yields when some fertilizers were replaced with biochar (Wu et al., 2024). Ghazaryan and Aleksanyan, 2024 recently examined the broader regional context of agricultural development and food security. They analyzed the sustainability of the agro-industrial complex in the EAEU countries using correlation and cluster analysis, revealing significant links between food security indicators and factors such as investment, technological development, and government support.

The appeal of biochar stems from its diverse applications, relatively simple production technology, and abundant feedstock availability (Abdullah et al., 2017). In a circular economy model, its sales potential can offset recycling system costs (Dafiqurrohman et al., 2016). The partial replacement of mineral fertilizers is a key application. While fertilizers effectively boost yields, their overuse can degrade soils and introduce contaminants (Sharma et al., 2022). Biochar can enhance nutrient availability and efficiency. For example, combining biochar with fertilizer significantly increases radish yield, which indicates a high substitution ratio (Niazi et al., 2023). Its porous structure also acts as a carrier for controlled nutrient release (Petrus et al., 2020). Depending on the feedstock, biochar itself can be nutrient-rich; for instance, manure-derived biochar can supply phosphorus (Wang et al., 2022). Studies have indicated that biochar can replace up to 20% of fertilizer mass without yield loss, highlighting its role in sustainable intensification (Yin et al., 2022).

Biochar also improves soil water retention, particularly in sandy soils, by modifying pore structure and increasing water-holding capacity—effects linked to higher crop yields (Santos et al., 2022; Li et al., 2021). Furthermore, it is a promising agent for soil remediation, capable of stabilizing contaminants such as heavy metals and adjusting soil pH to mitigate toxicity (Janiszewska-Latterini et al., 2025). It supports microbial communities by providing habitat and altering soil conditions (Blenis et al., 2023).

Emerging applications include its use as a livestock feed additive, where it can improve animal health and reduce emissions, although high-quality feedstocks are required for this purpose (Nair et al., 2023; Schmidt et al., 2019). The link between agricultural output and biochar potential is direct, as organic farming waste serves as the primary feedstock. Converting problematic waste streams, such as poultry manure, into biochar addresses disposal issues while creating a marketable product (Yoo et al., 2025), justifying the inclusion of agricultural sales volume as an indicator in our model. A relationship exists between the sales of main agricultural products and the potential biochar market because the organic waste required for biochar production is a direct byproduct of these agricultural organizations. Farmers may find biochar production attractive because it offers several benefits for a relatively small investment.

A comparison of our approach with international research highlights different methodological focuses. For example, Nematian et al., 2023 concentrated on a single production and marketing region, California's Central Valley, and emphasized the positive economic impacts of biochar production, including factors such as unemployment and diseases linked to environmental contamination from waste burning. John et al., 2025 took a different approach and analyzed scenarios for household-use pyrolysis units and their effect on biochar cost in Central Amazonia. Other research, such as that by Pavesi et al., 2024, focuses on the technical potential of biochar production from local organic residues without evaluating market demand. This study seeks to provide a more structured and comprehensive analysis of the potential consumption of biochar across Russia. Scaling biochar from a promising technology to a commercial reality requires spatially explicit, demand-side analysis to inform strategy and overcome market barriers such as informational opacity and underdeveloped policies (Trapero et al., 2025; Senadheera et al., 2025). Previous studies have focused on localized technical or economic aspects without providing a national comparative framework (Pavesi et al., 2024; Nematian et al., 2023). This study addresses this gap by developing the first integrated, nationwide ranking of regional potential,

thereby offering a foundational tool for strategic market development.

Against this background, assessing the biochar market's current state and prospects becomes particularly relevant. When assessing the current state of the biochar market in Russia, the lack of the necessary data becomes apparent, as the market is at an early stage of development and no large-scale studies on this topic have been conducted. The present study addresses one of the existing data gaps: an assessment of the potential demand for biochar in Russia represents the first step toward evaluating the market development prospects.

Further forecasting of the biochar market development in Russia should be based on current global experience. Existing indicators of the global biochar market indicate relatively rapid development. This can be illustrated by one of the most recent available reports on the global biochar market for 2023 (International Biochar Initiative and US Biochar Initiative, 2024), prepared by the International Biochar Initiative (IBI) in cooperation with the U.S. Biochar Initiative (USBI). Data are based on a survey of more than 1,000 respondents from 100 countries.

According to the report, the growth in production over the period 2021–2023 amounted to 91%, and the total production reached approximately 352 thousand tonnes by the end of 2023. In terms of value, the combined revenues of biochar producers, distributors, and equipment manufacturers exceeded USD 600 million in 2023, with a projected growth of USD 3.3 billion by 2025.

The key growth drivers identified include the need for land restoration, revenues from carbon crediting, and organic waste management challenges. Importantly, the respondents cited the need to develop high-quality end markets for physical biochar and to increase product awareness as the main barriers to market development. According to respondents, a significant issue is the limited adoption of standards for both biochar and its feedstocks. Accordingly, this study aims to address one of the existing challenges in the biochar market by creating an information base for relevant stakeholders. In this context, an assessment of potential regional biochar consumption represents a necessary first step toward evidence-based market development in Russia.

However, no prior study has systematically evaluated the regional biochar market potential across Russia using multi-criteria tools that integrate key drivers such as fertilizer substitution needs, irrigation demand, livestock development indicators, and soil degradation extent. Although this method has not been previously applied to the assessment of the biochar market, it has been established to evaluate the commercial potential of innovations and regional economic potential in contexts involving diverse, heterogeneous criteria. For instance, Sitnicki et al., 2021 presented it as a promising method for assessing innovation potential, acknowledging a degree of inherent subjectivity. Similarly, Imran and Nikolai, 2017 applied it to assess regional economic potential based on varied inputs, noting that expert evaluation is a key, albeit subjective, component. Given the heterogeneous nature of our regional data across the identified sectors, the fuzzy multiple-criteria approach is deemed suitable for integrating factors of different natures and weights to provide a structured, nationwide assessment of biochar market potential.

A systematic, multi-stage methodology is employed. First, primary agricultural application sectors for biochar are identified, with corresponding regional statistical indicators (X1–X6) selected as potential demand proxy variables. Second, a fuzzy multiple-criteria decision-making model is applied to integrate these heterogeneous criteria and calculate each region's composite potential index. Third, a complete ranking of 78 Russian regions is generated using this index. Finally, a complementary cluster analysis (K-means and hierarchical clustering) was performed to validate the results and uncover underlying regional profiles by grouping areas with shared socio-agroeconomic characteristics.

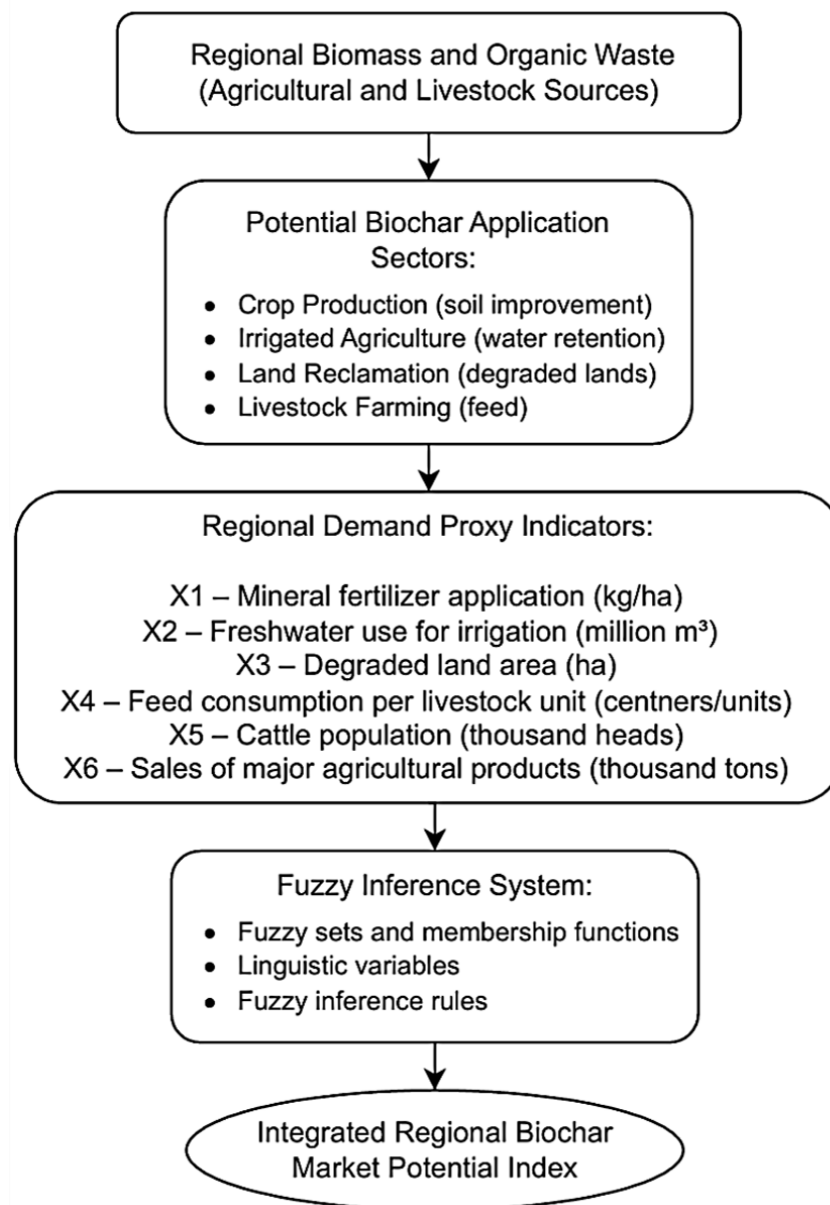
## 2. Methods

The fuzzy multiple-criteria approach was selected as the primary method for evaluating biochar's marketing potential. Smirnova, 2024 demonstrated the application of fuzzy set theory for assessing complex socio-economic phenomena, developing a risk assessment model for projects combining fuzzy sets with Bayesian networks to account for uncertainty and complex

relationships between multiple variables. This method was chosen to assess the relative "receptivity" of each region to biochar adoption—that is, to determine why Region A is more favorable for biochar sales than Region B.

To structure the assessment, a conceptual framework linking biomass sources, application sectors, regional indicators, and the fuzzy model was developed (Figure 1).

In this framework, potential demand for biochar is formed through its key application sectors: crop production, livestock farming, degraded land reclamation, and resource-efficient irrigation. As direct statistical data on biochar demand are absent, regional agricultural and land indicators (X1–X6) are employed as proxy variables reflecting the activity intensity and scale in these sectors. These indicators are integrated into the fuzzy multiple-criteria model to obtain a composite estimate of the potential for regional biochar sales.



**Figure 1** Conceptual framework for assessing the potential of the regional biochar market

A literature review identified key sectors where biochar is likely to be in demand.

1. Mineral fertilizer application per hectare of cropland

High mineral fertilizer application rates often indicate underlying soil deficiencies and an intensive agricultural system. There is a direct market link to biochar, as it can

significantly improve Nutrient Use Efficiency (NUE). Biochar amendments enhance soil organic matter, cation exchange capacity (CEC), and nutrient retention, thereby reducing leaching and increasing crop availability. This makes biochar a valuable complement to fertilization programs, especially in regions with poor natural soil fertility or high fertilizer costs (Alkharabsheh et al., 2021; Ding et al., 2016). Consequently, areas with high fertilizer inputs represent a strong potential market for biochar as a soil amendment to optimize these inputs.

## 2. Use of fresh water for irrigation

Regions with high irrigation demands face significant challenges related to water scarcity and cost. The capacity of biochar to improve soil water-holding capacity and hydraulic conductivity is well established. By enhancing soil moisture retention, biochar can reduce irrigation frequency and water requirements, contributing to greater water resilience (Mahmud et al., 2025). Therefore, a higher rank in irrigation water usage signifies a greater potential demand for technologies such as biochar that mitigate water stress and improve irrigation efficiency.

## 3. Degraded land area at the start of the reporting year

Land degradation, which affects more than 30% of the world's land area, is a critical threat to food security and ecosystem services. Biochar is widely recognized as a promising tool for soil restoration. It can be used to remediate contaminated soils, improve soil structure, increase organic carbon stocks, and restore fertility in degraded landscapes (Bolan et al., 2023). The larger the area of degraded agricultural or reclaimable land, the greater the market for biochar as a core component of land rehabilitation and sustainable land management strategies.

## 4. Feed consumption per conventional head of cattle

Beyond soil applications, biochar has emerged as a valuable feed additive in livestock production. Biochar can act as a detoxifying agent, improve feed efficiency, enhance nutrient absorption, promote animal health, and reduce methane emissions from enteric fermentation (Gaudaré et al., 2021). Feed consumption per head is a direct indicator of the intensity and cost of livestock operations, and improvements in feed efficiency have substantial economic benefits.

## 5. Cattle population

The total cattle population scales this potential, indicating the overall size of the livestock sector that could adopt biochar as a feed supplement. Together, these metrics identify regions where livestock systems would benefit most from the zotechnical advantages of biochar.

## 6. Sales of main agricultural product types by agricultural organizations

This aggregate indicator reflects the regional agricultural sector's overall scale, commercialization, and economic output. High sales volumes indicate the presence of large, market-oriented farm enterprises that are more likely to invest in innovative technologies to enhance productivity, sustainability, and product quality (Mahmud et al., 2025). It serves as a proxy for the agricultural sector's financial capacity and propensity to adopt new solutions, such as biochar, to secure and increase its output.

The initial evaluation of regional statistical data for these sectors revealed significant heterogeneity, precluding the use of traditional statistical methods. Although surveys of biochar production specialists are another common research method (Juuso et al., 2025; Salo et al., 2024), the fuzzy multiple approach was deemed more suitable for integrating factors of different natures and weights.

This study primarily focuses on the development of an approach for assessing the market potential of biochar. A previously adopted definition of biochar in accordance with the standard of the International Biochar Initiative (International Biochar Initiative, 2015) does not differentiate biochar into distinct grades based on intended application. The IBI standard establishes a clearly defined set of requirements that determine whether a given material can be classified as biochar.

Although the IBI standard does not introduce application-based grades, it does distinguish between testing levels A, B, and C according to carbon content and impurity thresholds, where level A represents the most stringent testing regime and level C the least demanding. This approach is not fully adequate for assessing the potential demand for biochar. A classification based solely on input and output control is insufficient given the high level of agricultural development, the substantial availability of biomass resources suitable for conversion into biochar in agricultural regions, and the diversity of application areas with specific quality requirements. More clearly defined grades are required, which are explicitly linked to end-use applications and the type and origin of the feedstock. Among these grades, one should be identified as the universal and adopted as a reference benchmark within the scope of the present study.

Because many regions currently lack a national biochar standardization system and the IBI classification does not meet the analytical needs of this research, the current version of the European Biochar Certificate (Carbon Standards International, 2025) may be referenced. A specific biochar grade must be selected as a reference value for further analysis to render the material conceptually concrete rather than abstract within the study framework. Under the EBC standard, biochar is classified into grades according to its intended end use and feedstock origin and quality requirements. Therefore, Table 1 presents a comparative analysis of biochar classes as defined by the EBC, including their application areas, feedstock requirements, and their linkage to the factors of the fuzzy-set approach employed in the model.

**Table 1** Comparison of biochar classes according to the European Biochar Certificate (EBC)

Grade	Intended use and application scale	Feedstock	Link to the model factors
EBC-FeedPlus	Feed additive for cattle or soil amendment. Applied in small quantities.	Exclusively clean plant-based biomass (in accordance with the EBC-positive list). Mineral additives are prohibited.	X4 (feed consumption) X5 (cattle population)
EBC-Agro (EBC-AgroOrganic)	Soil amendment and substrate. Applied in large volumes.	A broad range of plant residues, including crop residues and livestock by-products (e.g., manure and poultry litter).	X1 (fertilizer application) X2 (irrigation) X3 (degraded land) X6 (agricultural sales)
EBC-Urban	Urban landscaping and filtration in stormwater systems. Project-specific application volumes.	Plant-based biomass: limited feedstock mixing is permitted.	X2 (irrigation) X3 (degraded land)
EBC-Materials	Manufacturing of consumer goods (e.g., disposable tableware and textiles). The application volumes depend on the final product.	Plant-based biomass: the presence of impurities is permitted.	Not considered in the model
EBC-Basic	Industrial raw material. Applied in large volumes.	Widest range of feedstocks; permitted impurities.	Not considered in the model

The EBC-Agro biochar grade should be adopted as a reference benchmark for subsequent

analysis. We justify adopting the EBC-Agro biochar grade as a reference benchmark for subsequent analysis due to its large-scale use and comparatively permissive feedstock requirements. The positive list of eligible feedstocks for EBC-Agro biochar allows for the use of both plant-derived residues and livestock by-products (manure), which is critically important because the reference benchmark must encompass the widest possible range of regions in which biochar could potentially be produced and demanded in the future. The biochar of the EBC-Agro grade corresponds to the largest number of factors within the fuzzy-set approach applied in the model, which further facilitates a more robust justification for the subsequent allocation of weights. Accordingly, the biochar whose potential demand is assessed in this study should be defined as biochar of the EBC-Agro class or a material comparable to it in terms of physicochemical characteristics and feedstock base, as specified under the European Biochar Certificate. Therefore, all further discussion of biochar and its demand in the Russian Federation is based on the analysis of demand for this class of biochar.

### 3. Results and Discussion

The selected indicators and fuzzy scale used in the model are presented in the following sections, followed by the resulting nationwide ranking of regional biochar sales potential. Table 2 lists the factors used in this approach.

**Table 2** Factors for the fuzzy multiple-criteria analysis

Aspect	Name of the Factor	Code
Market potential of biochar	Mineral fertilizer application per hectare of cropland, kg	X1
	Freshwater usage for irrigation (reverse order), million m <sup>3</sup>	X2
	Degraded land area at the start of the reporting year, ha	X3
	Feed consumption per conventional head of cattle, centners of feed units	X4
	Cattle population, kilograms per head	X5
	Sales of main types of agricultural products by agricultural organizations, thousand tons	X6

The next step involved defining the fuzzy value scale, as detailed in Table 3. The calculated potential for biochar sales in a region is inversely related to the assessed risk; a lower final indicator value corresponds to a higher sales potential for biochar.

The Federal State Statistics Service (Rosstat) and the Federal Service for Supervision of Natural Resources (Rosprirodnadzor) provided the statistical data for this study. Data for factors X1, X2, X4, X5, and X6 were obtained from the appendix to the compilation "Agriculture in Russia 2023" (Rosstat, 2023), published on the Rosstat website. Factor X3 data were sourced separately from the 2-TP (reclamation) Report for 2024, available on the Rosprirodnadzor website (Rosprirodnadzor, 2024). These datasets required no additional processing because they were already in the requisite format. All calculations were performed using Microsoft Excel.

This study analyzes the expected structure of biochar consumption across Russian regions, independent of potential production centers. A critical step in applying the fuzzy multiple-criteria approach to assess the marketing potential of biochar is the accurate determination of weights for each factor. The most straightforward method is to assign equal weights, which is justified by the fact that the potential of biochar across these different applications has not been equally studied. However, this approach has a significant drawback: each application area may involve different biochar quantities, which could distort the regional results. Therefore, we determined specific weights for each factor based on available data regarding biochar use in each respective areas. Table 4 presents the weight distribution, and the factor values are shown in Table 5.

**Table 3** Fuzzy value scale

Value Set	Name	Definition
0–0.333	High Level	Characterized by intensive mineral fertilizer use, creating an opportunity to substitute with biochar to reduce chemical load; high irrigation water consumption, indicating a need for soil moisture retention; developed livestock sector with significant feed consumption; high volume of agricultural product sales; and large area of degraded land requiring reclamation.
0.167–0.5	Above Average	Moderate use of fertilizers; less frequent irrigation due to favorable soil and climate conditions; reduced feed consumption from a smaller cattle population; moderate demand for “green” products; and sufficient attention given to the reclamation of degraded lands.
0.333–0.667	Average Level	Low fertilizer application and sparse irrigation; small-scale farms with minimal cattle; low feed alternative usage or availability; low demand for eco-products; and a land-use structure that does not require large-scale reclamation of degraded lands.
0.5–0.833	Below Average	Reliance on traditional farming methods or underdeveloped agriculture; nearly no need for soil moisture retention; minimal demand for agricultural products; and no programs for restoring degraded lands.
0.667–1	Low Level	Fertile soils that preclude the use of fertilizer, a humid climate, suitable soils that eliminate the need for irrigation, or general underdevelopment of agriculture, an undeveloped livestock sector or the use of feed alternatives, a negligible demand for agricultural products, and minimal attention paid to land restoration.

We justify the assigned weighting factors for each variable based on the scale and nature of the primary agricultural applications of biochar. Factor X1 received a weight of 0.2 because biochar is extensively utilized as a soil amendment and land restoration agent, applications that require large quantities of material with comparatively lower quality thresholds (Guo et al., 2020). Similarly, factors X2 and X3, which are also weighted at 0.2, reflect the importance of biochar for enhancing soil water retention and rehabilitating degraded areas, both of which require significant volumes of material (Hossain et al., 2020).

Factor X6 was also assigned a weight of 0.2. Large-scale agricultural operations generate substantial organic waste streams that can be converted into biochar, thereby creating opportunities for large-volume production and application in a circular economy framework (Osman et al., 2022). Factors X4 and X5 were assigned a lower weight of 0.1. Although the use of biochar as a feed additive provides benefits for animal health and methane emission reduction, its application in animal husbandry involves substantially lower per-unit volumes and demands stricter quality and safety specifications for the final product (Schmidt et al., 2019).

Consequently, the weighting scheme distinguishes between high-volume applications with moderate quality requirements—such as soil enhancement and waste valorization (weights of 0.2)—and low-volume, high-specification applications, such as animal feed supplementation (weight of 0.1) (Man et al., 2020).

Subsequently, the values were normalized using mean normalization. This choice was motivated by the high heterogeneity and extreme value ranges in the regional data across Russia’s vast territory. Normalization by the mean provides a more stable and intuitive measure of relative deviation for our context because it is less sensitive to outliers that could disproportionately distort the variance.

**Table 4** Weight distribution of factors.

Factor	Weight	Justification
X1	0.2	The use of biochar as a soil additive or for land
X2	0.2	reclamation requires large quantities of biochar with lower
X3	0.2	quality requirements.
X4	0.1	Biochar is used in livestock farming as a feed additive,
X5	0.1	which involves small quantities and high-quality
		requirements.
X6	0.2	Agricultural organizations generate large amounts of waste
		and may be interested in recycling it into biochar for sale.

**Table 5** Factor values (for the Leningrad Region, including Saint Petersburg, and the Russian average) for the Leningrad region.

Risk factor	X1	X2	X3	X4	X5	X6
Risk	51.9	3.8	9650.67	25.2	171.9	1022.58
Mean value	66.2	76	30648.12	29.4	215.9	1240.05

Thus, the calculated biochar sales potential for the Leningrad region is 0.661, placing it at the boundary between the "average" and "below average" levels. This indicates that the region has a relatively low projected demand for biochar. The same calculation methodology was applied to all other regions of the Russian Federation.

To demonstrate the application of the developed fuzzy multi-criteria approach, we conducted a comprehensive case study of the Russian Federation. This case study applies the approach to generate the first nationwide ranking of regional biochar sales potential. The analysis resulted in a comprehensive ranking encompassing 78 of the 82 regions of the Russian Federation that were initially selected. Calculations were omitted for certain regions due to a lack of available data (Magadan Region, Chukotka Autonomous Okrug, and Sevastopol) or because their statistical data were consolidated with another region (for example, the data for St. Petersburg is combined with that of the Leningrad Region). Table 6 presents the top 15 positions of the ranking. For clarity, regions belonging to the same federal district are color-coded in the "Region" column.

**Table 6** Top 15 Russian regions ranked by biochar sales potential and membership distribution across potential categories (Very High, High, Medium, Low, Very Low)

Nº	Region	Value of the potential indicator	Very high	High	Medium	Low	Very low
1	Krasnodarskiy krai	0.1856	0.882427	0.117573			
2	Rostov region	0.3203	0.075958	0.924042			
3	Saratov region	0.3352		0.987088	0.012912		
4	Stavropol region	0.3734		0.758235	0.241765		
5	Krasnoyarsk region	0.3963		0.621008	0.378992		
6	Novosibirsk region	0.4389		0.365677	0.634323		
7	Volgograd region	0.4396		0.361939	0.638061		
8	Kaliningrad region	0.4429		0.342039	0.657961		
9	Voronezh region	0.4784		0.129276	0.870724		
10	Astrakhan region	0.4796		0.121992	0.878008		
11	Republic of Tatarstan	0.4898		0.06127	0.93873		
12	Ryazan region	0.4983			0.010464	0.98954	
13	Tyumen region	0.5011			0.993535	0.00646	
14	Lipetsk region	0.5032			0.980792	0.01921	
15	Bryansk region	0.5071			0.76878	0.23122	

The analysis identifies the Krasnodar Territory as having the highest sales potential, while

the Kostroma Region ranks the lowest. An examination of the top 15 regions reveals that the greatest demand for biochar is concentrated in the federal districts of Southern (4 regions), Central (4 regions), Siberian (2 regions), and Volga (2 regions). Figure 2 illustrates the geographical distribution of the regions with the highest biochar sales potential. Each region is highlighted in green and labeled with its ranking number.



**Figure 2** Geographical distribution of the top 15 biochar sales potential regions. The ranking numbers correspond to 1. Krasnodar Krai, 2. Rostov Oblast, 3. Saratov Oblast, 4. Stavropol Krai, 5. Krasnoyarsk Krai, 6. Novosibirsk Oblast, 7. Volgograd Oblast, 8. Kaliningrad Oblast, 9. Voronezh Oblast, 10. Astrakhan Oblast, 11. Republic of Tatarstan, 12. Ryazan Oblast, 13. Tyumen Oblast, 14. Lipetsk Oblast, 15. Bryansk Oblast.

The map highlights regions with the highest estimated market potential, showing their concentration in the southern, central, and parts of the Siberian federal districts. A K-means clustering algorithm was applied to identify homogeneous groups of regions based on their biochar market potential indicators. The optimal number of clusters was determined to be three ( $k=3$ ) using the elbow method, which evaluates the within-cluster sum of squares against the number of clusters to be three ( $k = 3$ ). The 78 regions were partitioned into three distinct clusters with clear socio-agro-economic profiles (Table 7). The K-means clustering analysis successfully delineated three distinct regional profiles with clear implications for the development of the biochar market.

**Table 7** K-means clustering results ( $k = 3$ )

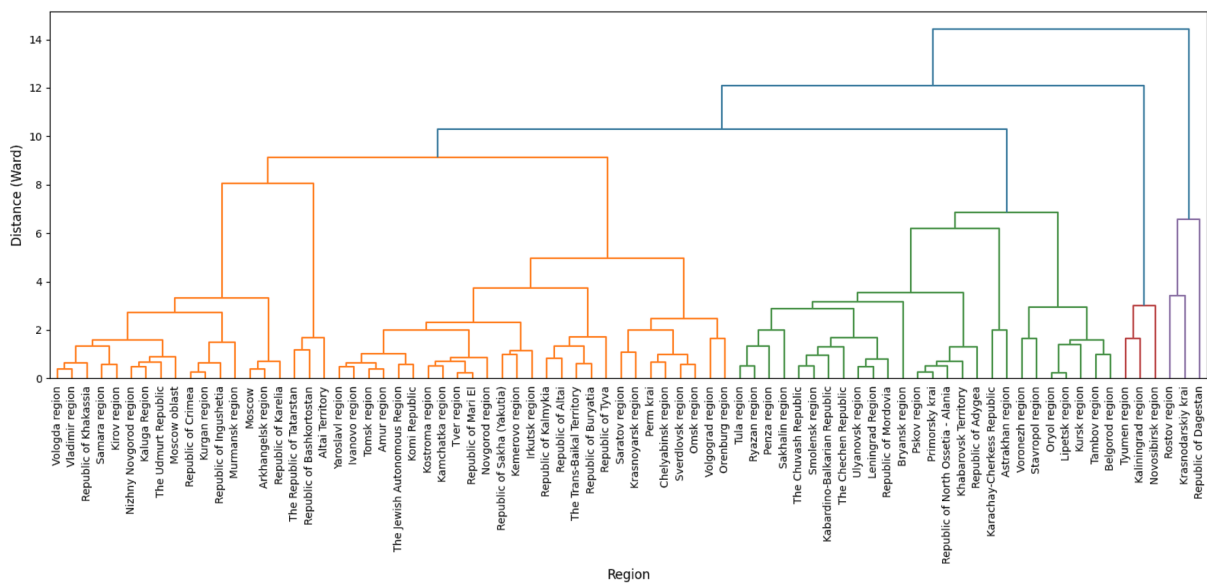
Cluster	Number of Regions	Mean X1	Mean X2	Mean X3	Mean X4	Mean X5	Mean X6	Examples
0	72	67.64	27.44	11,844.83	29.88	201.72	1,100.75	Altai Territory, Belgorod region, Republic of Tatarstan
1	3	95.08	1,487.30	36,595.18	31.93	711.62	5,220.89	Krasnodarskiy krai, Republic of Dagestan, Rostov region
2	3	71.82	2.09	523,525.58	31.65	275.31	1,262.86	Kaliningrad region, Novosibirsk region, Tyumen region

Cluster 0 forms the broad, general market foundation. The Volga region and the Urals comprise 72 regions from European Russia and represent the mainstream agricultural landscape. The study is characterized by moderate values for mineral fertilizer use (X1), irrigation water demand (X2), and livestock intensity (X5), alongside a significant area of degraded land (X3). The primary value propositions for biochar in this cluster are large-scale soil restoration and input efficiency enhancement (fertilizers, water). Success in this market will depend on supplying

a large customer base with cost-effective, bulk-grade biochar.

Cluster 1 includes three southern regions (Krasnodar, Dagestan, and Rostov). characterized by extreme irrigation demand and the highest agricultural output, this cluster forms a solution-oriented market with a premium. The potential of biochar is tied to its role as a water conservation technology and a yield-enhancing amendment in high-productivity systems. Market penetration is highly sensitive to demonstrable return on investment (ROI) and performance metrics. In contrast, Cluster 2 (Kaliningrad, Novosibirsk, and Tyumen) is defined by an exceptionally vast area of degraded land, whereas other factors, such as irrigation needs, are comparatively low. The overwhelming driver for biochar in these three regions is large-scale land rehabilitation and reclamation. While the potential for volume use in restoration projects is significant, the low irrigation need diminishes one key value proposition. Opportunities may also exist for biochar as a feed additive, given the concentrated livestock profile.

Hierarchical cluster analysis was performed to visualize the structural relationships and relative similarities between all regions. The resulting dendrogram (Figure 3), constructed using Ward's linkage method, confirms and elaborates on the K-means-identified grouping patterns.



**Figure 3** Hierarchical clustering dendrogram

The dendrogram reveals several major clusters, color-coded for clarity. The orange cluster on the left is the largest and most homogeneous, combining most regions from European Russia and the Volga, Nizhny Novgorod, Republic of Tatarstan, and Sverdlovsk regions. Regions within this cluster merge at relatively low linkage distances, indicating high similarity in their indicator profiles. A green cluster in the center-right primarily unites regions of Siberia and the Far East, such as the Republic of Sakha (Yakutia), Khabarovsk Territory, Irkutsk region, and Novosibirsk region. The blue cluster on the right, forming at a high linkage distance, consists predominantly of North Caucasian republics, such as the Chechen Republic, Republic of Ingushetia, and Republic of Dagestan. Finally, a small red/pink cluster at the far right, merging at the highest distance, is the most distinct and includes the Tyumen region.

The K-means and hierarchical clustering analysis results demonstrate a strong and logical convergence with the earlier fuzzy logic assessment of biochar sales potential. This alignment between two distinct methodological approaches validates the identified market segmentation and reinforces the findings' credibility.

The fuzzy logic model identified Krasnodar Krai and Rostov Oblast as having the highest potential. Independently, clustering analysis groups these regions into Cluster 1, which is characterized by intensive agriculture, significant water demand, and high agricultural output. This methodological convergence strongly confirms that they are primary targets. The Republic of Dagestan, also a member of Cluster 1, is assessed with more moderate potential by the fuzzy

model. This indicates an internal gradation within the intensive agricultural cluster, where Dagestan's specific profile shifts its potential toward the medium range.

Regions such as Kaliningrad, Novosibirsk, and Tyumen Oblasts (Cluster 2) are rated having medium potential by the fuzzy model. Clustering reveals their distinctive profile: an extensive area of degraded land (X3), but lower scores in other drivers, such as irrigation. This explains why their potential, while significant, is specialized toward land restoration rather than being broadly high across all value propositions.

In terms of potential, Cluster 0 is not homogeneous, while the fuzzy logic results reveal a clear internal gradient. Thus, regions within Cluster 0 that border on Cluster 1 characteristics (e.g., Saratov, Stavropol, and Volgograd Oblasts) demonstrate high potential, the central core of Cluster 0 (e.g., Bryansk and Lipetsk Oblasts, and the Republic of Tatarstan) aligns with medium potential, and the peripheral regions of Cluster 0 (e.g., Arkhangelsk and Vologda Oblasts) are marked by less intensive agriculture and correspond to low potential.

This study provides a comprehensive, nationwide overview of biochar demand, revealing that regions with vastly different economic profiles can exhibit similarly high potential, exemplified by the Stavropol and Krasnoyarsk territories (ranked 4th and 5th, respectively). The Stavropol Territory is a predominantly agricultural region with an above-average demand for water and fertilizers and high agricultural product sales. In contrast, the Krasnoyarsk Territory shows a high potential primarily due to its extensive areas of degraded land requiring reclamation and its developed livestock sector.

The application of the fuzzy multiple-criteria approach in this study had certain limitations, partly due to data gaps and assigned factor weights. For instance, the livestock development factors were assigned the lowest weights due to the high-quality requirements for feed-grade biochar, even though some regions outside the top 15, such as the Omsk Region, exhibited above-average indicators in this category. The selection and weighting of factors can be contextualized using similar studies. For example, Thengane et al., 2021 identified soil amendments, filter elements, and feed additives as the most promising biochar markets in California. Although the use of biochar as a filter element was beyond the scope of this study, it represents a promising avenue for future market research. Furthermore, Zilberman et al., 2023 conducted a study on supply chains and concluded that biochar would be adopted primarily in regions with degraded or infertile soils, a finding that aligns with our results.

This analysis enables the strategic siting of production facilities or the development of integrated biochar production and consumption clusters by quantifying the relative biochar potential of different regions (Ahmed et al., 2025; Adhikari et al., 2024). The spatial patterns revealed, such as the concentration of high-potential regions in agriculturally intensive areas, directly inform market logistics. These regions typically have high local biomass feedstock availability, favoring decentralized production and minimizing transport costs. In contrast, regions with specialized potential (e.g., for land reclamation) may require more complex supply chain solutions.

Empirical studies on controlled-release formulations support the role of biochar in enhancing fertilizer efficiency. Petrus et al., 2020 demonstrated that when 20% biochar was used as a coating material for ureic fertilizer, it significantly slowed nitrogen release with an effective diffusivity of  $2.85 \times 10^{-8}$  cm/s<sup>2</sup>, confirming the potential of biochar to improve nutrient use efficiency and reduce fertilizer losses.

The market potential of biochar is inherently linked to its physicochemical properties, which vary significantly by feedstock and production process. Cifriadi et al., 2025 demonstrated that biocarbon derived from tamarind wood exhibited mechanical properties in rubber composites comparable to petroleum-based carbon black N990 at 15 phr loading, while cassava starch-derived biocarbon showed chemical similarity to commercial fillers. Such findings underscore that feedstock selection directly influences biochar quality and its suitability for specific applications.

Beyond conventional applications, biochar can be engineered through chemical modification for specialized uses. Ma'rifah et al., 2019 demonstrated a one-step synthesis method for pro-

ducing sulfonated biocarbon acid catalysts from palm empty fruit bunches, achieving a twofold increase in H<sup>+</sup> ion capacity and successful incorporation of -SO<sub>3</sub>H functional groups. Such modifications expand the potential application scope of biochar into industrial catalysis beyond soil amendment and feed additive.

Several studies have identified key barriers to market development, including a lack of universal standards, limited industrial-scale data, and underdeveloped government policies (Senadheera et al., 2025; Salo et al., 2024). This study's data on consumption potential helps mitigate the problem of incomplete information and increases market transparency, which is itself a recognized obstacle to growth (Trapero et al., 2025). Consequently, the results of this research establish a foundation for further investigation into Russia's biochar market.

#### 4. Conclusions

This study aimed to assess the marketing potential of biochar in the Russian Federation. The findings indicate that a significant proportion of the country's regions exhibit a low potential for biochar sales. The suitability of a region for biochar market development depends on its specific regional challenges and predominant economic activities. Furthermore, the intended application dictates distinct requirements for the consumed biochar quality and volume. The fuzzy multiple-criteria approach successfully integrated these aspects into the potential assessment. The primary output of this research is a list of Russian regions ranked based on their biochar sales potential. These results can serve as a foundation for further market studies and provide valuable insights for strategic planning by both businesses and government agencies. The fuzzy logic model quantifies the degree of regional potential, whereas the cluster analysis explains the structural causes by grouping regions with common socio-agro-economic profiles. This combined analytical outcome moves beyond mere identification to provide actionable insight, forming a solid foundation for recommending differentiated regional strategies for developing the biochar market. High-potential regions (Cluster 1) warrant focused commercial strategies, mid-potential regions (Clusters 0 core 2) require targeted programs (e.g., restoration incentives), and low-potential regions (Cluster 0 periphery) may be deprioritized or approached with long-term development frameworks.

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#### Author Contributions

Conceptualization, S.G.; methodology, A.Z. and D.R.; validation, S.I.; formal analysis, A.Z. and M.B.; investigation, M.E.; resources, D.R.; data curation, S.I.; writing original draft preparation, A.Z. and D.R.; review and editing, S.G. and S.I.; visualization, M.E.; supervision, S.G.; project administration, D.R. and M.B.; funding acquisition, D.R. and A.Z. All authors have read and agreed to the published version of the manuscript.

#### Conflict of Interest

The authors declare no conflicts of interest.

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