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Original Research Article

Unlocking Bio-Based Potential: Assessing Biomass and Nutrient Availability for Sustainable Development

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ABSTRACT

This paper aims to offer actionable insights and recommendations for steering regions, particularly agricultural hubs, towards sustainable development in alignment with EU standards, while fostering resilience in the face of evolving challenges. A comprehensive survey with key stakeholders and detailed review of relevant national and local policies and documents were conducted in order to assess biomass and nutrient availability of Strumica region as a case study. The analysis identified primary agricultural and forestry residues, secondary residues from processing industries, and municipal biowaste as valuable resources. Furthermore, the paper highlights initiatives focusing on composting and mycelium-based products, emphasizing their environmental and economic benefits. Survey findings reveal the current state of waste management in processing industries and underscore the need for regulatory compliance and improved practices. Additionally, the paper examines nutrient availability in fertilizers and compost, stressing the importance of nutrient management in soil fertility and crop productivity. Recommendations include research on biomass utilization, policy support for modernization, promotion of composting practices, and collaboration with regional platforms.

KEYWORDS

Bioeconomy, Biomass availability, Primary and secondary residues, Nutrient management, Composting, Strumica region.

INTRODUCTION

The shift toward a bio-based economy is crucial for achieving sustainability objectives, as it involves substituting fossil fuels with renewable resources like biomass [1]. As a renewable energy source, biomass has garnered attention for its role in reducing greenhouse gas emissions

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and minimizing waste, thereby supporting environmental sustainability [2]. Agricultural, forest residues, food waste, and industrial byproducts hold particular importance within bioeconomy strategies, as they contribute to both circular economy principles and energy generation goals [3], [4]. The European Union (EU) has established itself as a leader in advancing bio-based economies, incorporating these strategies into broader initiatives such as the Green Deal and the Circular Economy Action Plan [5]. These efforts aim to maximize natural resource efficiency, minimize ecological harm, and stimulate local economic growth. A critical aspect of the EU's bioeconomy strategy involves reusing agricultural waste, which has shown potential to improve soil health, enhance crop yields, and reduce dependence on synthetic fertilizers. However, researchers argue that successful implementation of bioeconomy strategies requires effective policies, advanced technologies, and active stakeholder participation, all of which differ across European regions [6].

The modern bioeconomy integrates various pillars and aims to maximize the potential of all types of sustainably sourced biomass, including crop residues, industrial by-products, food waste, and organic municipal waste, by converting them into high-value bio-based products and processes [7]. Recent analyses suggest that biomass resources have notable potential to supply large shares of global energy demands, with agriculture playing a crucial role in enhancing future bioenergy potential [8], [9]. Globally, the annual production of agricultural waste, including crop residues, animal residues, and waste from the distribution and processing of agricultural products, is estimated to be around 998 million tons, with organic waste comprising 80% of this total [10]. The direct use of agricultural waste, such as compost for soil improvement, contributes to minimizing landfill environmental impacts, reducing greenhouse gas emissions and balancing the carbon cycle.

The transition to a bio-based economy requires efficient nutrient cycle closure and sustainable resource management to address both economic and environmental challenges. Current dependence on mineral fertilizers threatens food security and exacerbates climate change, highlighting the urgent need for improved nutrient use efficiency and reduced losses to support a circular economy and mitigate environmental impacts [11].

However, the bioeconomy involves a complex network of stakeholders-including government institutions, industry, environmental organizations, and civil society-all contributing to the bioeconomy supply chain. Recently, at the European level there has been a growing interest and awareness among stakeholders. Yet, challenges persist in regulatory structures, production capacity, commercialization, and industry standards, underscoring the need for large-scale research, commercialization strategies, and education to drive the bioeconomy sector forward [12], as well as for establishing standardized guidelines for bio-based products for fostering market trust and improving the competitiveness of bio-based solutions [19].

Similar challenges arise in the development of the bioeconomy in North Macedonia, particularly due to the absence of a dedicated Bioeconomy Strategy, and the county's primary focus on decarbonizing the energy sector [13], [14] and expanding renewables [15], [16]. Also, the existing strategies often fail to address key metrics such as resource scarcity, underscoring the need for frameworks that balance innovation with environmental and social considerations.

On a national scale, agriculture is an important economic segment, employing 13.9% of the active population, with crop production engaging over 50% of agricultural workers. Nevertheless, the sector faces numerous challenges. such as climate change and ageing workforce, with a mere 4% of agricultural holders under the age of 35. Educational attainment within the sector varies, with a significant portion having completed only secondary or primary schooling, which contributes to the low level of resilience of the agriculture sector [18].

While national-level efforts for bioeconomy development are emerging, the Strumica region has positioned itself as a frontrunner in the bioeconomy-driven rural development, having mapped and quantified biomass availability from primary and secondary agricultural residues.

Situated in the southeastern part of North Macedonia, the Strumica region, located, stands as a prominent agricultural stream within the country. With its 321.9 km² and strategic proximity to two EU member countries, it holds an important position for sustainable agricultural development. Its diverse landscape, consisting of plains and hilly terrains, supports 24,000 hectares of agricultural land, predominantly arable fields and gardens. The region cultivates a balanced mix of grain and vegetable crops alongside high-quality tobacco varieties, reinforcing its importance in the national agricultural sector [17].

Furthermore, with a population of 49,555 inhabitants, Strumica enjoys favorable climatic conditions and abundant natural resources, standing for a sustainable economic and bio-based development[†]. It ranks among the top municipalities in the Livelihood Vulnerability Index (LVI), reflecting its strong adaptive capacity while considering regional disparities in development, resources, demographics, and socio-economic aspects [18]. Agriculture and animal husbandry, as the main economic drivers, are accounting for 40% of the economic activity, followed by the textile and wood industries, each contributing 25% and 13%, respectively. Moreover, with around 10% share for the food industry, the region has several modern facilities for processing primary agricultural products, including canned vegetables, meat, and tobacco, further boosting its economic diversity [20].

Despite its strengths, Strumica region still faces issues, such as small-scale farming, rural depopulation, and a lack of agricultural education and expertise. These hurdles hamper the sector's competitiveness and productivity, particularly in light of emerging climate change impacts. Moreover, the situation is exacerbated by a shortage of landfills and an ineffective waste management system, especially for the bio-waste, mainly due to an inadequate legal framework and poor enforcement of existing regulations.

This paper examines biomass and nutrient availability in the Strumica region, focusing on agricultural, forestry and processing residues for sustainable use. It evaluates key nutrients essential for soil fertility and crop productivity, aiming to foster bioeconomy development. Additionally, the study explores the engagement of processing industries, their interest in the findings, and their readiness to adopt new practices. Ultimately, this paper provides actionable insights to guide the Strumica region towards sustainable agricultural development, aligned with EU standards and resilience to future challenges.

LITERATURE REVIEW

This literature review examines existing research on biomass and nutrient availability, regional challenges, and policy measures promoting sustainable bioeconomy practices. It provides a critical analysis of relevant studies published in peer-reviewed journals, focusing on methodologies used to assess biomass potential, nutrient management strategies, and policy frameworks for regional sustainability. Additionally, it contextualizes Strumica's regional bioeconomy within broader EU policies relevant to North Macedonia, drawing on comparative studies to highlight best practices and potential policy alignments.

Agriculturally rich regions like Strumica in North Macedonia are well-suited for bio-based initiatives. Organic materials, including food waste and agricultural residues, can be converted into valuable products that align with resource efficiency and sustainability goals [21], [22]. Composting is a cost-effective method for managing organic waste, as it degrades various biodegradable materials such as agricultural residues, food waste, and urban solid waste while contributing essential nutrients to the soil [23]. Despite this potential, challenges such as inadequate infrastructure, inconsistent policy support, and limited awareness among farmers have hindered adoption in parts of Southeast Europe. It is important to stress the importance of localized bio-based value chains, showing that regional systems focused on composting and

[†] SSO: Census data 2021 - North Macedonia, link

nutrient recycling can improve resource efficiency and support sustainable agriculture [24]. Composting, in particular, is gaining traction as it reduces waste, cuts methane emissions, and enriches soil with organic matter, making it a valuable practice for circular bioeconomies [25]. To foster a circular economy in line with compost quality assessment, a deep understanding of the fates of nutrients and carbon in the composting process is essential to achieve the co-benefits of value-added and environmentally friendly objectives [26]. Moreover, as fertilizer prices continue to rise globally and food waste generation escalates, composting offers a sustainable solution to replenish soil minerals while addressing organic waste management challenges [27].

Nutrient management is another cornerstone of the bioeconomy. With increasing pressure to reduce the use of chemical fertilizers, alternatives like compost and biofertilizers provide environmentally friendly ways to boost soil fertility [28]. Factors such as temperature, pH, moisture content, and the carbon-to-nitrogen (C:N) ratio significantly influence compost quality, affecting its role in sustainable agriculture and regional bioeconomy initiatives [23]. Additionally, recent studies highlight the need for improved composting models that account for the fates of key nutrients-C, N, P, and K-to enhance predictive accuracy and optimize compost application in agriculture [26]. Recycling nutrients through composting is particularly effective for creating a more balanced agricultural ecosystem [29]. Biomass potential and utilization have gained increasing attention in global research, particularly in the context of energy applications and circular economy initiatives. Studies indicate a sharp rise in biomass-related research, especially after 2012, with significant contributions from countries like China, India, the USA, Germany, and the UK.

This growing body of research underscores the importance of optimizing biomass utilization strategies, including composting, for improved resource efficiency and sustainability [30]. However, achieving circularity in bio-based systems requires localized strategies that integrate policymaking, market access, and education for stakeholders [31].

MATERIALS AND METHODS

A comprehensive array of data sources and reports to analyze biomass potential, waste management and environmental conditions in the Strumica region and broader areas of North Macedonia are reviewed for the purposes of conducting this paper. Key documents such as [20] and [17] are detailing biomass status quo, local waste management strategies, and outlining environmental action plans for the upcoming years. Additional data comes from statistical reports on agricultural areas, crop production, and forestry by municipalities, provided by the State Statistical Office (SSO). Studies on composting potentials, fertilizer use, and agricultural by-products further inform the analysis. Complementing these sources are reports on waste categories, food losses, and regional studies on agricultural residues. Notable documents include [32] and [33] providing information on the composting and crop residues for the Strumica region and broader. The integration of these diverse data points enables a thorough assessment of environmental and agricultural practices, contributing to an in-depth understanding of biomass availability, waste management and sustainability efforts in the region.

Furthermore, this paper employs a two-tiered approach to assess biomass availability, moreover primary agricultural and forestry residues alongside secondary residues from processing industries. Additionally, it investigates nutrient availability to provide comprehensive insights into the potential for sustainable bio-based value chains. The above-mentioned materials provide the overview on the primary agricultural residues, representing the demand, whereas the secondary agricultural residues assessment was obtained through a comprehensive questionnaire, representing the supply. This demand/supply mapping offers a holistic overview of the resources available for developing bio-based initiatives. To closely understand the actual situation regarding biowaste generated by key industries, a questionnaire was created and shared with industry and business sector in Strumica region. The survey included 10 questions focused on the company's operations, the types of waste produced, and the management of that waste, such as:

- Name of factory/industry/enterprise
- Activity (Canning of vegetables and fruits, Meat processing, Processing of (non)alcoholic beverages, Dairy processing, Oil processing, Tobacco processing and fermentation, Milling and baking industry, small production facilities for sweets and similar products, Wood processing industry or Other)
- Type of enterprise (micro, small, medium or large)
- What kind and how many residues are produced by the factory?
- What is the quality of the residues from production/processing?
- Are you currently using the residues from production/processing? If yes, please specify for what purpose.
- Do you dispose of residues with biological origin? If so, where?
- Is there organized collection of such waste and is it charged?
- Do factories receive a fee for these residues, or do they have to pay to be collected? At what price?
- Is there currently enough control for waste management?
- Would you join an initiative for handling bio-waste, e.g., organized collection of this type of waste for the production of compost or other bio-based products?

The questionnaire was sent to over 25 industry representatives, ensuring broad coverage across various production sectors. The responses were collected, cleaned, and analyzed using both quantitative and qualitative methods. Descriptive statistical analysis was employed to identify trends and patterns in waste generation, management, and utilization practices. Additionally, qualitative responses were examined to extract insights into industry perceptions and willingness to participate in bio-based waste initiatives. This methodological approach provides a comprehensive understanding of biomass residue availability and waste management challenges, facilitating informed decision-making for sustainable resource utilization in the region.

RESULTS AND DISCUSSION

The Strumica region is strategically focusing on enhancing a single value chain centered around composting. This initiative entails a thorough exploration of various biomass streams suitable for composting, including their availability, quality, and spatial distribution. Additionally, the region is considering another potential value chain that involves the production of packaging and insulation materials from agricultural residues and mycelium.

A significant portion of agricultural residues and biodegradable waste from processing industries currently ends up in non-standard landfills, amounting to approximately 22,000 tons annually [34]. However, by repurposing these materials for compost production, the region aims to mitigate waste accumulation and reduce methane emissions from landfills. Composting not only addresses environmental concerns and reduces the waste quantity that ends up in landfills, but also enhances soil health, reduces erosion, conserves water, and minimizes household food waste. The initial focus of this paper is on agricultural residues and biodegradable waste from primary producers and food processing industries. Expansion to include communal waste from residential and commercial sectors may follow if sufficient data can be gathered, despite the challenges posed by the lack of a regional bio-waste separation system.

On the output side, the composting value chain presents opportunities for collaboration, such as collecting agricultural residues from local farmers for use in a nearby biogas plant. This plant, with a capacity of up to 2MW, generates energy and also produces bio-based fertilizers, benefiting other farmers in the region ‡.

Another potential bio-based value chain under consideration involves mycelium-based packaging and insulation materials. These innovative products utilize regional agricultural residues and mycelium as bonding agents, offering benefits such as biodegradability, sustainability, flame resistance, lightweight, shock absorption, durability, and flexibility. Moreover, the production process is environmentally friendly, generating no wastewater and requiring significantly less energy compared to traditional solutions. However, the viability of this value chain depends on the maturity of the market for advanced bio-based products.

In the context of composting, nutrient availability is crucial for improving soil fertility and supporting plant growth. Compost enhances soil's ability to retain and deliver essential nutrients, such as nitrogen (N), phosphorus (P), and potassium (K). Proper nutrient balance, particularly the carbon/nitrogen (C/N) ratio, is essential for successful composting processes. Additionally, parameters like phosphorus (P), sulfur (S), calcium (Ca), and trace elements influence cell metabolism and overall compost quality [33].

The benefits of recycling biodegradable residues extend beyond waste reduction, aligning with sustainable and circular principles such as cleaner production, zero-waste, and a bio-based economy. By implementing these value chains, the Strumica region aims to foster economic growth, environmental stewardship, and social well-being while contributing to regional and global sustainability goals.

Assessment of primary agricultural and forestry residue biomass availability

The assessment of biomass availability in Strumica region involves a comprehensive review of data on local, regional, and national levels. Various aspects such as agricultural and forest areas, crop production, waste generation, and municipal biowaste are analyzed to identify the potential for bio-based solutions. The data presented in figures and tables provide a detailed overview of the biomass resources available in the region.

Agricultural Area and Crop Production. The assessment begins with an examination of the agricultural area in Strumica. **Figure 1** illustrates the distribution of agricultural land by category of use, highlighting cultivated areas, meadows, vineyards, and orchards. The data from the MAKStat database from 2022 reveal that out of 23,646 hectares of agricultural land, 8,137 hectares are cultivated, primarily comprising arable land and gardens.

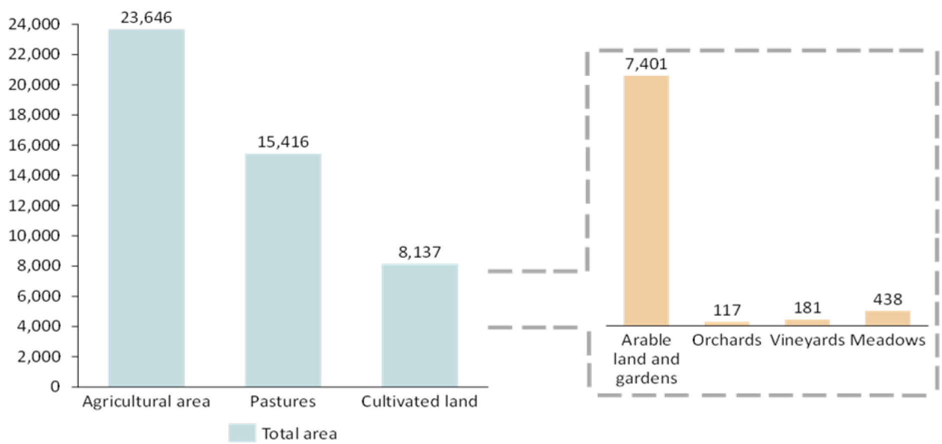

Figure 1. Agricultural area by category of use Source: MAKStat database

Further analysis focuses into the production of principal agricultural crops, including grain, forage crops, vegetables, and fruits. **Figure 2** and **Figure 3** provide insights into the sown and

‡ Feroinvest: Saramzalino biogas power plant, link

harvested areas, total production, and yield of various crops. Notably, alfalfa emerges as the highest-yielding forage crop, while cucumbers, tomatoes, and peppers dominate vegetable production.

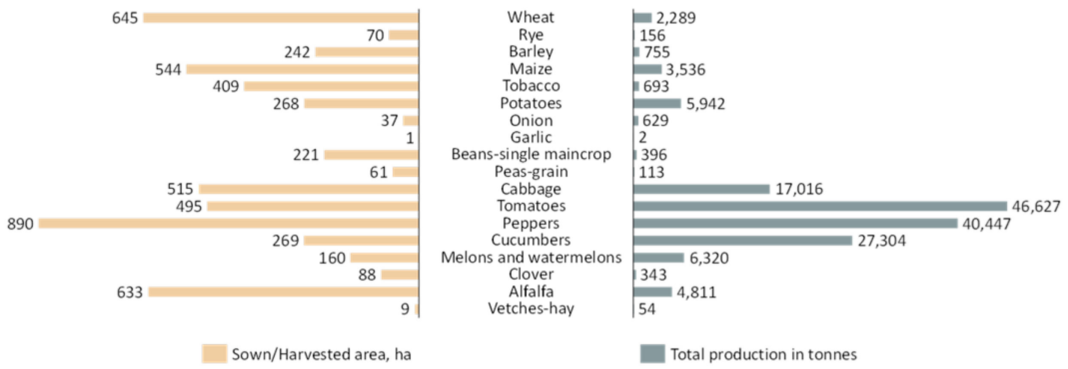

Figure 2. Area and production of grain and forage crops and vegetables

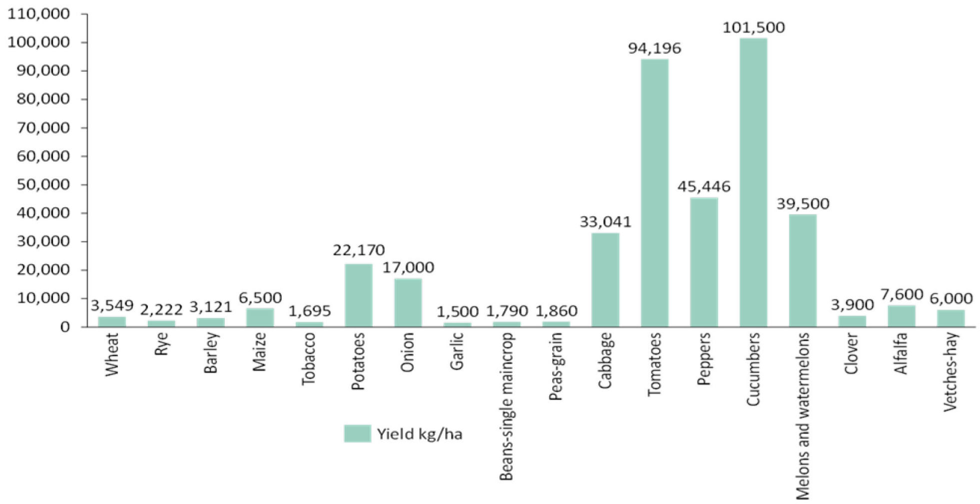

Figure 3. Grain and forage crops and vegetables yields Source: MAKStat database

In fruit production, apples lead in the number of fruit-bearing trees and total production, as shown in **Figure 4**.

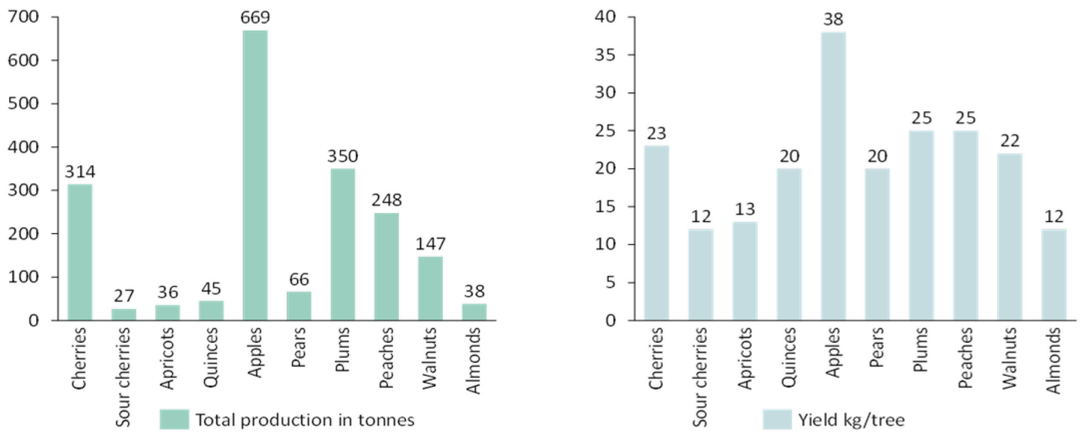

Figure 4. Production of fruit Source: MAKStat database

Although wine production isn't Strumica's main focus, the region still boasts a considerable output, making it a category worth monitoring. In 2022, the harvested area totalled 170 hectares, with total number of vines and bearing vines accounting for 946,000 and 914,000, respectively. The total production reached 5,780 tons, averaging 34,001 kg/hectare, showcasing the region's potential for composting purposes[§].

Forest Residues. The assessment also considers forest residues as a potential biomass resource. **Figure 5** presents an overview of the forest area by tree types in the South-East region, totalling 142,739 hectares in 2022, with broad-leaved species being most represented. Additionally, afforestation efforts and gross felled timber residues are outlined, indicating the availability of forest biomass for utilization.

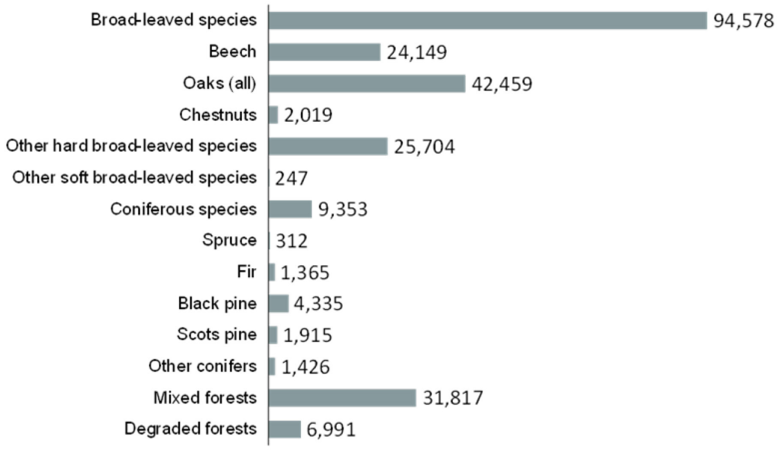

Figure 5. Forest area by type in South-east region Source: MAKStat database

Municipal Biowaste. Another important aspect of biomass availability is municipal biowaste from households and the commercial sector. **Figure 6** illustrates waste generation by categories in tonnes on a national level for 2020, with households being the primary contributors.

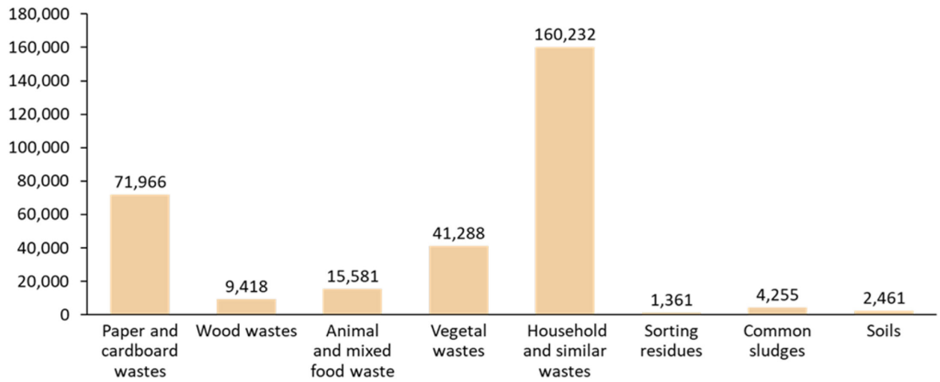

Figure 6. Amount of waste, by waste categories Source: MAKStat database

Focusing specifically on municipal waste in the South-East region, **Figure 7** provides data on waste fractions in Strumica, highlighting the significant portion of organic waste **[32]**.

[§] SSO: Area and production of vineyards, link

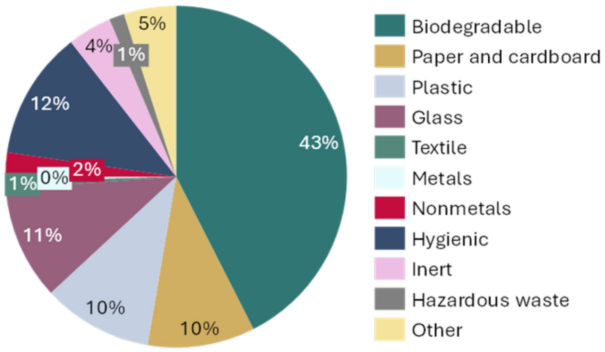

Figure 7. Quantities of municipal waste divided by fractions (in tonnes / year)

Estimation of Bio-Waste Production. The data shown below offer different approaches to estimate bio-waste production based on sown areas of agricultural crops and total crop production.

Table 1 presents the sown area of various crops and potential organic residues quantities, providing insights into the amount of waste generated by different crop types. Largest potential quantities of residues come from cereals, garden crops and industrial crops **[20]**.

Table 1. Sown area of agricultural crops and potential organic residues quantities in Strumica

Agricultural crops	Sown area (ha)	Organic residues (t)
Cereals	2383	4766
Garden crops	1640	3280
Fodder crops	480	960
Industrial crops	580	1160
Oil crops	38	76
Fruit crops	120	240
Vine crops	137	274

Table 2 estimates bio-waste production by considering waste percentages based on production levels and post-harvest handling and storage **[35]**. The amount of waste from fruits and vegetables production is dominant, amounting to more than 35.000 tonnes annually.

The assessment also touches upon waste management initiatives in Strumica. The municipality is in the process of establishing a waste selection system for the residential sector, beginning with plastic separation. However, the lack of biowaste separation poses challenges for accurate data gathering and efficient waste management.

Overall, the assessment of biomass availability in Strumica underscores the diverse range of biomass resources present in the region, including agricultural, forest residues, and municipal biowaste, with a substantial potential and should be harnessed for promoting sustainable agricultural growth in the region. Furthermore, it can facilitate income diversification by leveraging these resources effectively, so Strumica can explore opportunities for bio-based solutions by introducing good practices and potentially generate new green jobs.

Table 2. Estimate of bio-waste production

	Assumed percentage of waste (production + handling and storage)	Total production (tonnes)	Estimate waste production (tonnes)
Cereals (wheat, barley, oats, maize)	2% + 4%	7429	445
Roots and tubers (potatoes and potatoes –interfiled)	20% + 9%	5942	1723
Fruit and vegetables (onion, garlic, beans-single maincrop, peas-grain, lentil, cabbage, tomatoes, peppers, cucumbers, melons and watermelons, cherries, sour cherries, apricots, quinces, apples, pears, plums, peaches, walnuts, almonds)	20% + 5%	140794	35198

Survey Findings on Organic Waste Output in Processing Industries

Examining the biomass availability from secondary residues within processing industries in Strumica region illustrate the obstacles, aforementioned in the introduction of this paper, encountered in waste management. A questionnaire distributed to 16 most relevant subjects (industries, companies and the vocational high school for agriculture in Strumica, which stands out as the only institution of its kind in the region), provided valuable insights into the types and quantities of waste generated, as well as existing waste management practices. The distribution reveals that 53% of the entities are small-scale, 33% are medium-sized, while micro and large-scale entities each account for 7%.

Among the surveyed industries, a diverse range of sectors was represented, including canned vegetables and fruits, wood processing, beverage production, meat processing, and milk processing. The majority of these enterprises classified their waste into various categories, with a notable portion generating biowaste such as vegetable and fruit residues, gardening and plant residues, and residues from the refining processes. Additionally, mixed waste types, including cardboard packaging, plastic packaging, and non-compliant milk, were reported. The geographic distribution of the surveyed processing industries in the Strumica region is illustrated in **Figure 8**, providing a visual representation of the locations of the interviewed entities.

Despite the diversity in waste generation, a significant percentage (73%) of industries reported not benefiting from their residues, with only a few utilizing their waste for heating purposes, secondary product production, or selling it to specialized waste management companies. However, some industries emphasized to take into account the environmental impact of the waste they produce, by providing biowaste to local farmers or repurposing it for composting, thereby contributing to the regional bioeconomy development.

The current waste management status quo in Strumica reveals a lack of full compliance with regulatory frameworks and plans at the national and regional levels. While larger industries collect their bio-waste in separate containers for removal by public waste management companies, the overall control and enforcement of waste management practices are deemed insufficient by approximately 60% of the stakeholders surveyed.

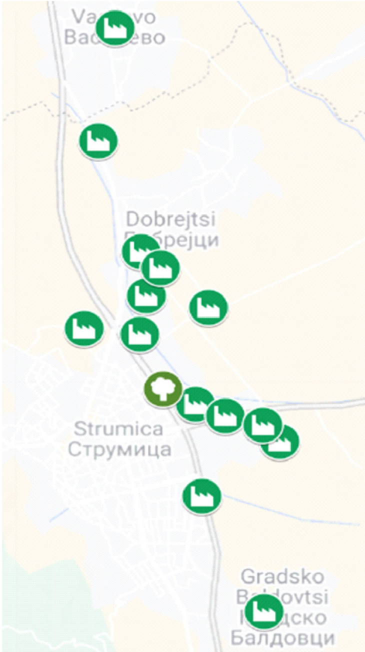

Figure 8. Map of Surveyed Processing Industries in the Strumica Region

Financial considerations also play a role in waste management, with industries being charged for waste disposal services depending on the waste type. However, there are instances where industries, particularly those producing alcoholic and non-alcoholic beverages, receive reimbursement for bio-waste selection, indicating potential incentives for improved waste management practices.

The findings from the survey underscore the need for enhanced waste management control and regulatory compliance in Strumica. Encouragingly, nearly 80% of surveyed industries expressed interest in participating in activities related to bio-waste management, highlighting a willingness to engage in innovative solutions for waste reduction and resource optimization.

The assessment of biomass availability from secondary residues in processing industries provides valuable overview into the current state of waste management practices in Strumica. By addressing regulatory gaps, enhancing waste management control, and leveraging initiatives like the SCALE-UP project, Strumica can move towards in a more sustainable and efficient path, maximizing the potential of biomass resources for economic and environmental benefits.

Availability of nutrient in fertilizers and compost

In general, the availability of nutrients in fertilizers and compost plays a crucial role in supporting soil health and productivity and decreases the need for synthetic fertilizers, whose prices have been steadily rising in recent years due to factors such as the war in Ukraine and the energy crisis. Nutrients are categorized into primary macronutrients (nitrogen, phosphorus, and potassium), secondary macronutrients (calcium, magnesium, and sulfur), and micronutrients (chlorine, iron, boron, manganese, zinc, copper, nickel, and molybdenum). Compost, a key component, contributes to soil improvement by enhancing its structure and facilitating nutrient absorption by plants. Although compost doesn't immediately enrich the soil with essential elements, it fosters a conducive environment for nutrient uptake, leading to improved soil balance.

Several factors influence the composting process of organic waste, including particle size, microorganisms, aeration, porosity, moisture content, temperature, pH value, nutrient content, and the absence of toxic substances. Optimal conditions for composting include a C/N ratio of 25:1, appropriate levels of phosphorus and potassium, and a balance between brown and green mass components. Phosphorus, essential for cell growth and development, is the second limiting nutrient for crops after nitrogen, while potassium is crucial for various metabolic processes in plants [33].

This study compiles and synthesizes available data on nutrient availability in fertilizers and compost, integrating findings from previous research with a case study conducted in the Strumica region. Rather than conducting new laboratory or field analyses, the paper presents a comparative review of existing studies to illustrate the advantages of bio-based fertilizers in the context of regional agriculture.

A study within the Strumica River Watershed Restoration Project extensively examined soil properties, including water-physical and chemical aspects, and the presence of calcium carbonate. Bio-based and mineral fertilizers were also explored, highlighting their role in soil fertility enhancement. Organic matter, rich in phosphorus, potassium, and organic nitrogen, decomposes in the soil, contributing to its structure and nutrient content. Bio-based fertilizers, such as farmyard manure, green manure, and compost, provide accessible nutrients through microbial decomposition, enhancing soil fertility and productivity. As shown on **Table 3**, if properly chosen, green manure can introduce approximately 100 kg N/ha, 30 kg P/ha, and 130 kg K/ha into the soil [36].

Table 3 . Green manure crops

Crop	Rooting Depth (cm)	Enrichment with N (kg/ha)
Lupine	60-230	160-300
Peas	30-90	80-130
Beans	80-130	75-130
Red Clover	100-200	75-130
Alfalfa	200-300	290-390
Oats	/	35-90
Mustard	/	35-90

Mineral fertilizers contain biogenic elements categorized as simple and complex, physiologically acidic, neutral, and alkaline. They are classified based on the active material into nitrogen, phosphorus, and potassium, with common examples including calcium ammonium nitrate, ammonium sulfate, ammonium nitrate, sodium nitrate, calcium nitrate, urea, and calcium cyanamide for nitrogen fertilizers. Phosphorus fertilizers include superphosphate, Thomas phosphate flour, and triple superphosphate, while potassium fertilizers comprise potassium sulfate, potassium carbonate, and potassium chloride. Calcium fertilizers like limestone, unquenched lime, and saturational manure are also widely used.

In 2021, North Macedonia recorded a fertilizer use of 50.5 kg per hectare of arable land, significantly lower than the world average of 161.5 kg per hectare[**]. The price for imported mineral fertilizer is 20 euros per 25 kg package, while locally produced bio-based fertilizer from biowaste residues costs 15 euros per 25 kg package or even 10 euros per 30 kg package[††, ‡‡]. Therefore, locally produced bio-based fertilizer is cost-effective, environmentally friendly, and positively impacts climate change mitigation efforts. It is recommended to use these bio-based fertilizers instead of minerals ones, as they reduce costs and promote sustainability. By adopting locally sourced options, industries will benefit from lower expenses for waste disposal, fostering a more eco-friendly and economical approach to

[**] The Global Economy, North Macedonia: Fertilizer use, link
[††] Eko Habitat: Bio-based fertilizer price, link
[‡‡] Sinpeks: Mineral fertilizer price, link

managing agricultural residues. This shift not only supports local economies but also enhances waste management practices and reduces environmental impact.

A significant portion of agricultural residues and bio-waste from processing industries in Strumica ends up in landfills rather than being utilized for soil improvement on farmers' fields. This highlights the need for enhanced utilization within the regional bioeconomy to better manage these resources. In the Strumica region, there are already positive examples related to composting. While there is significant potential for expanding composting efforts, financial support and scaling up are necessary to encourage more farmers to engage in composting practices. By investing in this area, the region can enhance waste management, improve soil health, and promote sustainable agricultural practices. Supporting and expanding composting initiatives will not only benefit individual farmers but also contribute to the overall sustainability and resilience of the local agricultural sector.

As part of the SCALE-UP project, a study visit was organized in Strumica to showcase successful waste management practices. A family-owned composting plant in municipality of Novo Selo in the Strumica region, operational for four years, annually produces 5000 cubic meters of certified bio-based compost. The facility, covering four hectares, sources raw materials from various organic sources, including herbs, flowers, fruits, and reeds. The composting process involves agronomists and skilled machine operators, with a turnaround time of six months per cycle.

The success story of the composting plant underscores the importance of comprehensive research aimed at improving the nutritional aspects of compost, particularly focusing on macronutrient content. By prioritizing research and implementing sustainable waste management practices, Strumica can enhance its agricultural productivity and soil fertility.

CONCLUSION

The assessment of biomass potential, demand-supply mapping and nutrient availability in the agricultural sector of the Strumica region highlights both challenges and opportunities for sustainable development. With an estimated biomass potential of 10,000 to 40,000 tons per year of fresh material, the region possesses significant resources for bio-based initiatives and economic growth. However, uncertainties persist regarding biomass utilization, with up to 22,000 tons annually being discarded.

A structured, holistic approach is essential to maximize biomass utilization. **Table 4** summarizes key challenges and solutions, emphasizing improved knowledge sharing, policy support for modernization, promotion of composting practices, and collaboration with regional platforms. Strengthening local knowledge, assessing market potential, and analyzing the feasibility of composting initiatives will enable stakeholders to better leverage available resources. These efforts align with project activities, including training sessions, best practices exchange, and enhancing the expertise of the vocational high school for agriculture through student competitions. Additionally, advocating for policies that incentivize modernization and sustainable farming practices is crucial. Active engagement from municipalities and farmers is necessary, as demonstrated by the strong interest generated through the innovation challenge and training sessions on the business aspects of biomass utilization.

The promotion of composting practices, supported by pilot plants, can enhance sustainable waste management practices at both household and industrial levels. Diverting organic waste from landfills and encouraging compost use in agriculture can improve soil quality, reduce reliance on mineral fertilizers, and enhance nutrient recycling. The municipality should take the lead in establishing and supporting pilot plants, while companies can integrate composting within their operations. The public waste management enterprise should also facilitate organic waste collection and processing, ensuring an integrated approach to waste management. Collaboration with regional platforms and participation in initiatives like the SCALE-UP project further strengthens knowledge-sharing and partnership building. Notably, SCALE-UP training sessions have already benefited 1,200 participants across various regions, demonstrating their tangible impact. Inspired by successful models from Andalusia and Sweden, the regional platform can serve as a powerful mechanism for fostering innovation in the bioeconomy sector.

Table 4. Key Challenges and Recommended Solutions for Biomass Utilization in the Strumica Region

Identified Problem	Recommended Solution	Suggested action step
High biomass potential underutilized	Promote biomass utilization through composting, bio-based initiatives, and innovative projects.	Farmers turn agricultural residues into compost instead of discarding them.
Significant biomass waste	Encourage composting practices with pilot plants at household and industrial levels.	A local farm sets up a small composting facility to process crop waste.
Lack of farmer awareness of biomass utilization	Organize training sessions, practical workshops, and awareness programs in collaboration with vocational schools.	Farmers attend workshops on turning leftover crops into compost.
Limited policy support for modernization	Advocate for policy incentives, including tax breaks and subsidies for composting and bio-based solutions.	Government offers tax breaks for farmers investing in composting equipment.
Weak collaboration among stakeholders	Strengthen partnerships through regional platforms, government support, and SCALE-UP project participation.	Farmers collaborate with a university to research biomass utilization.
Limited vocational training in biomass utilization	Enhance agricultural high school programs with student competitions and innovation challenges.	Students compete in a science fair to develop biomass-based innovations.
Lack of financial incentives for sustainable farming	Implement grants, subsidies, and tax benefits for bio-based technologies and composting equipment.	Farmers receive subsidies for purchasing composting machines.
Inefficient waste management systems	Engage public waste management enterprises in organic waste collection and processing.	Municipality partners with a waste company to improve organic waste collection.
Insufficient private sector involvement	Introduce regulatory frameworks and economic incentives for industries (e.g., food & wood processing) to adopt bio-waste solutions.	A wood processing factory starts using waste materials for biomass energy.
Missed economic opportunities in bioeconomy	Develop business plans and support programs to commercialize bio-based innovations.	A farmer creates a business plan to sell compost made from agricultural waste.

Industry participation can be encouraged through tax incentives and regulatory frameworks that promote bio-waste initiatives, particularly in wood processing and food processing factories. National-level policy adjustments- such as amendments to environmental and economic development programs-could facilitate these incentives, while municipalities can advocate for their integration them into local waste management strategies. Adjustments to the Law on Waste Management and sustainable development programs could provide the necessary framework to implement for effective implementation. Aligning economic incentives with environmental objectives, will stimulate investment in sustainable waste management practices and bio-based solutions, contributing to both economic growth and environmental sustainability.

Unlocking Strumica's full biomass potential requires targeted training programs for farmers on efficient biomass utilization and composting techniques. Practical workshops, organized by the vocational high school for agriculture in collaboration with local extension services could provide hands-on learning opportunities. Financial incentives-such as subsidies for composting equipment or grants for biomass-based technologies-would further encourage adoption of sustainable practices. The municipality, in partnership with the Ministry of Agriculture, Forestry and Water Economy, could oversee these initiatives. Additionally, integrating tax incentives for sustainable farming practices and subsidies for bio-based innovations into national policies, with the involvement of the Ministry of Finance and the Ministry of Environment and Spatial Planning could provide long-term support.

By implementing these measures, Strumica can advance sustainable waste management, support economic growth, and foster bio-based innovation, creating a resilient and resource-efficient agricultural sector.

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