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REVIEW

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Agroforestry systems and forest resources as a potential for sustainable energy development in the western Balkan region

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Abstract

Background The significance of sustainable energy development and the battle against climate change continues to grow each year. Countries exhibiting unsustainable fossil fuel consumption practices are actively pursuing strategies to decrease import dependency and mitigate pollution through innovative approaches in their energy policies. In this context, the countries aim to rely primarily on their own direct and indirect energy resources. Identifying and using new resources to secure clean energy represents one of the strategic approaches to achieving the established objective. The focus is on using resources that have the greatest potential and whose exploitation aligns with the economic capabilities of the countries. The Western Balkan countries have relied on substantial coal use for decades, resulting in significant pollution emissions, but they lack the capacity to invest in specific renewable energy alternatives. Upon examining the potential, it is evident that the most significant opportunity for acquiring clean energy in the region is found in the biomass sourced from forestry and agriculture. The exploitation of agroforestry systems facilitates carbon sequestration, in addition to various beneficial outcomes. The Western Balkan region boasts abundant forests and lands conducive to the implementation of agroforestry systems, which hold considerable, yet untapped, potential for clean energy generation. This paper aims to review and synthesize knowledge regarding agroforestry in the Western Balkan countries, assess the capacity of forest and agroforestry resources, and identify essential activities that can promote their more intensive yet sustainable use.

Main text The potential of using agroforestry as a source of bioenergy has not been sufficiently explored in the Western Balkans. Therefore, the research was conducted by examining the scientific literature and pertinent statistical indicators. The literature search covered 85 scientific references, encompassing conference proceedings, abstracts, and additional valuable resources. This expanded reference base provided a solid foundation for analyses and discussions on agroforestry in the Western Balkan region. Following that, an analysis of the forest potential and prior experiences in energy production from forest biomass in five Western Balkan countries was conducted and presented. The analysis revealed that the share of forests and forest biomass in the region's total territory is the lowest in Albania (37.5%) and the highest in Bosnia and Herzegovina (61.1%). This signifies a substantial biomass potential that is underused, while agroforestry systems exist in rural regions only in a few areas that satisfy the requirements of individual households. The systematic collection of biomass from the agroforestry system and its usage for clean energy generation are at a minimal level. Furthermore, the examination of the regulatory framework demonstrates

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the importance of developing policies and incentive mechanisms that recognize agroforestry as a method of obtaining biomass and ensuring food and water security. Therefore, a model of the supply chain and the main elements of the agroforestry–agriculture–energy nexus is proposed as a starting point for enhancing cross-sectoral cooperation and the sustainable use of forest resources.

Conclusions The main findings presented in this paper could benefit the Western Balkan countries seeking to enhance sustainable energy development approaches. Given the substantial forest and land resources and favorable climatic conditions in the Western Balkan region, forthcoming strategies must incorporate the formulation and implementation of effective agroforestry policies, as well as their integration into energy policy and sustainable development plans.

Keywords Agroforestry, Biomass, Bioenergy, Wood biomass, Western Balkans

Background

Western Balkan (WB) countries face a multitude of challenges when it comes to climate change and sustainable energy development, as well as the sustainable management of all natural resources [1]. The reasons for these challenges are diverse, but they can primarily be traced back to the region's historical development, characterized by the intensive use of fossil fuels (particularly coal) and low electricity prices, which are often considered a social category [2]. In such a context, there is little initiative to increase energy production from renewable sources, even when the potential is high. Despite some progress made in this area, the overall impact on sustainable energy development remains minimal. Energy efficiency is low [3], and greenhouse gas emissions often have hazardous implications. The outbreak of the Ukrainian crisis further exacerbated issues related to sustainable development as the priority shifted toward ensuring sufficient energy supply [4, 5]. Renewable energy production has especially lost momentum in the WB countries, which are at a lower stage of economic development. Nevertheless, the high pollution levels (especially air pollution) across all countries in the region exert significant pressure on decision-makers at all levels to explore and consider all possible options for sustainable energy production [6, 7]. Implementing agroforestry as a potential solution for generating energy in a sustainable manner is certainly one of the viable options.

Agroforestry is an agroecological practice that integrates elements of agriculture, forestry, biodiversity conservation, and various other fields [8]. It constitutes a multi-purpose land use system that can be conceptually defined as the integration of trees with crops and/or livestock [9]. For land users at all levels (farmers, agroforestry practitioners, land managers and planners, policymakers and government agencies, etc.), it is a dynamic system that supports and diversifies output while providing social, economic, and environmental advantages [10]. While agroforestry has been a longstanding practice in Europe for centuries, it has only recently gained attention from scientific communities as part of finding solutions to combat climate change and use all natural resources in a sustainable manner [11, 12].

Based on data collected from around the globe over the course of at least 40 years, agroforestry has demonstrated a strong track record as a sustainable land management technique for enhancing soil quality, while in recent decades it has also been considered a potential source of renewable energy [13].

Bioenergy is crucial in agroforestry because it provides a renewable energy source from agricultural and forestry residues, reducing reliance on fossil fuels. Based on their practices and configurations, different agroforestry systems can distinguish themselves as bioenergy sources with varying potential (Table 1). Nair [14] proposed a classification of agroforestry systems into four main categories (groups) that combine trees or woody shrubs with:

- Annual or perennial crops (agrisilvicultural systems);
- Pastures and grazing animals (silvopastoral systems);
- Crops and animals (agrosilvopastoral systems)
- Non-pastoral animal species ("other systems") such as combinations of fish, shrimp, or bees with trees or shrubs providing habitat or fodder

The interactions and outcomes of agroforestry systems depend on the system type, practice, and configuration, as well as the species of trees, shrubs, crops, and livestock involved [15].

A consideration of agroforestry and forestry biomass potential fully aligns with the Western Balkan countries' commitment to membership in the European Union (EU). The Western Balkan (WB) countries and European Union leaders signed a Sofia Declaration on the Green Agenda for the Western Balkans (2020). This document sets out comprehensive goals for the WB, including:

Table 1 Classification of agroforestry systems based on the type of components, according to Nair [14]

Type of system	Major groups of components			
	w: woody	h: herbaceous	f: fodder for grazing	a: animals
Agrisilvicultural systems: crops—including shrub/vine/tree crops—and trees				
Improved fallow	Fast-growing preferably leguminous	Common agricultural crops	/	/
Taungaya	spp. for plantation forestry	Common agricultural crops	/	/
Alley cropping	Fast-growing, leguminous, vigorous regrowth/ coppicing	Common agricultural crops	/	/
Multilayer tree gardens	Woody components of varying form and growth habits	Sometimes shade tolerant spp.	/	/
Multipurpose trees on crop lands	Multipurpose and fruit trees	Common agricultural crops	/	/
Plantation crop combinations	Timber, fruit, and multipurpose service trees; plantation crops like coffee, cacao, coconut, rubber, black pepper, etc	Usually shade tolerant spp.,	/	/
Homegardens	Fruit trees predominate; also, other woody species, vines, etc	Shade tolerant agricultural species	/	/
Trees in soil conservation and reclamation	Multipurpose and/or fruit trees	Common agricultural species	/	/
Shelterbelts and windbreaks, live hedges	Combination of tall-growing spreading types	Agricultural crops of the locality	/	/
Fuelwood production	Firewood species	Agricultural crops of the locality	/	/
Silvopastoral systems: trees + pasture and/or animals				
Trees on rangeland or pastures	Multipurpose; of fodder value	/	Present	Present
Protein banks	Leguminous fodder trees	Present	Present	/
Plantation crops with pastures and animals	Plantation crops	/	Present	Present
Agrosilvopastoral systems: trees + crops + pasture/animals				
Homegardens with animal production	Often dominated by fruit trees, woody vines	Shade-tolerant vegetables and medicinal plants	/	Minor species, specialty markets
Multipurpose woody hedgerows and riparian buffers	Fast-growing and coppicing fodder shrubs and trees	Agricultural crops	/	Grazing and browsing animals
Apiculture with trees on farmlands	Melliferous tree species of complementary phenology	Bee-pollinated crops, e.g., cucurbits	/	/
Aqua agroforestry	Trees and shrubs producing leaves and fruits for fish	/	/	Fish, shrimps, etc
Multipurpose woodlots	Multipurpose, leguminous, timber, fruit, etc	Shade-tolerant crops	/	Various

- Enhancing the legal and strategic framework;
- Co-financing the implementation of innovative pilot programs; and
- Obtaining more funding to support scale-up initiatives that contribute to the green transformation.

To achieve these goals, the document outlines five key pillars that form the foundation of its strategic approach: (1) climate action, decarbonization, energy efficiency, and the promotion of green industries; (2) fostering a circular economy to enhance resource efficiency and promote industrial symbiosis; (3) depollution of the environment with an emphasis on improving air quality; (4) preserving and investing in biodiversity and ecosystems; and (5) promoting sustainable food systems for sustainable rural livelihood [16].

Nowadays, the EU recognizes and supports agroforestry through the Common Agricultural Policy (CAP) [17]. Specifically, agroforestry is part of the EU Green Deal and its components, such as the Farm to Fork Strategy and the EU Biodiversity Strategy for 2030. The EU Forest Strategy for 2030, within the mentioned Biodiversity Strategy, includes a goal of planting 3 billion more trees, many of which should be outside forests [18].

However, the specific application of agroforestry and the use of forest potential for energy production are practices that have been insufficiently investigated or scientifically addressed in the Western Balkan countries. The Western Balkan countries—Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, and Serbia [19] (Fig. 1)—are taking different steps toward joining the European Union. However, before joining, they must align and implement their legislation with the EU "acquis", or the accumulated legislation, legal acts, and court decisions that constitute the body of the EU laws, with the chapters related to ecology and energy being particularly problematic [20].

Considering that agroforestry is classified as an agroecological practice [8], Šeremešić et al. stated that in WB nations, agroecology began to gain attraction in the 1990s after being connected to organic agriculture and ecology [22]. They also stressed how this, combined with environmental protection, a diet rich in wholesome foods (whole grains, fruits, vegetables, seafood, eggs, etc.), and a clearly defined legislative framework, aided popularization of agroecology. As a result, agroecology has been recognized as a crucial sustainable system that WB can use to achieve sustainable development goals (SDGs) and as an alternative to traditional agriculture, considering that monocultural agriculture results in soil degradation, reduced biodiversity and increased economic risk.

While the EU Green Deal primarily targets EU member states, its principles and objectives are highly relevant to the WB countries. The implementation of agroforestry systems and practices in the WB countries, guided by the EU Green Deal, offers a comprehensive approach to achieving sustainable agriculture, energy, and environmental stewardship. By enhancing

Fig. 1 Western Balkan countries [21]

biodiversity, mitigating climate change, improving soil and water management, providing economic benefits, and fostering regional stability, agroforestry can play a pivotal role in the sustainable development of the WB region.

Main text

Agroforestry systems as new potential for bioenergy

Energy efficiency and sustainability are key goals of modern society, especially in the context of global climate change and the growing demand for renewable energy sources. One of the significant approaches that can contribute to these goals is agroforestry. Agroforestry systems present new potential for bioenergy by using biomass from tree and crop residues, offering a sustainable energy source that complements agricultural production. This practice combines agriculture and forestry to create sustainable and multifunctional ecosystems. The WB region has significant potential for the development of agroforestry practices due to the high percentage of forest, agricultural, meadow, and pasture areas. A summary of the land cover and use in the WB countries was provided by Zdruli et al. [20] (Table 2). The aforementioned data shows that considerable percentages of the land are occupied by forests and places with forestry biomass, including shrubs (Albania 37.5%, Bosnia and Herzegovina 61.1%, Montenegro 59.6%, North Macedonia 45.4%, and Serbia 32.2%). On the other hand, the percentage of agriculture land is also high (particularly in Albania at 24.3%, Bosnia and Herzegovina at 24.1%, and Serbia at 31.4%). This clearly indicates the area's significant potential, given that wood is one of the earliest renewable energy sources.

Cvjetković [23] identified agroforestry as a critical component of sustainable development, capable of substantially contributing to energy sustainability by integrating biomass as a renewable energy source. Malico et al. [24] emphasized the positive effect of using forest and agricultural residues for bioenergy production, which can be important for rural areas of WB. According to World Bank predictions, biomass consumption will double by 2050, which indicates the importance of biomass as an energy source [24]. In the WB countries with high energy demand, agroforestry offers a viable approach for establishing sustainable energy systems that diminish reliance on fossil fuels.

Using proven agroforestry practices helps reduce energy use, diversify revenue streams, and provide environmental benefits for farms, countryside, and communities [25]. With fewer inputs, agroforestry generates more biomass per unit area than monocultures. It lessens the requirement for irrigation, pesticides, and fertilizers and shields fields from the stronger storms and droughts that come with climate change [26]. Sharma et al. [27] state that trees can serve as feedstocks for the synthesis of a variety of bioenergy products. For instance, solid biomass can be used to generate electricity, charcoal, and firewood. Lignocellulosic biomass can be used to produce ethanol, while oilseeds can be used to produce liquid biofuels like biodiesel. Leftover materials like oilseed cake and leaves can be used to produce biogas [28]. Finally, by integrating bioenergy into agroforestry, the WB region can address environmental challenges such as deforestation and soil degradation while contributing to energy security and sustainable development goals.

Given this background, it is necessary to document the realities, possibilities, and potentials of agroforestry in the WB countries, which have been examined for the first time in the literature. The goals of this paper are to (1) provide a comprehensive description of the agroforestry systems and practices used in the WB region, with a focus on agroforestry as the potential for sustainable energy development of the said region, and (2) suggest problem solution matrix analysis as support to targeted issues related to agroforestry in the WB countries.

Methods

Data collection

To enhance the comprehensiveness of our literature review and broaden the scope of references, we conducted thorough research through the David Lubin Memorial Library of the Food and Agriculture Organization (FAO) (available at: https://www.fao.org/library/

Table 2 Summary of land use/land cover for the WB countries according to Zdruli et al. [24]

Countries	Pop. Million	Area km^2	Agriculture land (%) (cropland and permanent crops)	Forest and areas with forestry biomass including shrubs (%) (against total territory)	Permanent meadows and pastures (%) (against total territory)
Albania	2.8	28,748	24.3	37.5	16.6
BiH	3.3	51,130	24.1	61.1	12.7
Montenegro	0.6	13,888	0.8	59.6	17.5
North Macedonia	2.0	25,436	17.8	45.43	31.6
Serbia	6.9	88,407	31.4	32.2	7.6

libraryhome/en/). Using the library's advanced search interface, which facilitates a unified search across its extensive collections of digital (e-books, e-journals, and research databases) and print materials, we were able to access a wealth of resources. Our search strategy involved the application of new keywords and their variations, including "tree biomass", "Western Balkan Forest*", "fast-growing tree species Western Balkan*", "Serbia", "Albania", "Bosnia and Herzegovina", "Macedonia", "poplars", "willows", and "agroforest*". This approach enabled us to identify 85 new references, encompassing conference proceedings, abstracts, and other valuable resources. This expanded reference base significantly enriches our manuscript, providing a solid foundation for our analysis and discussions on agroforestry in the Western Balkan region.

Using the ScopusTM platform (last accessed on September 07, 2023), a review of publications published between 2000 and 2023 was the first step in the analysis. For each of the WB's member states—Albania, Montenegro, Bosnia and Herzegovina, North Macedonia, and Serbia—we conducted a separate search for the term "Agroforest*" in the abstract, keywords, and title. Second, we searched the ScopusTM platform for "Agroforestry practice*", "Agroforestry system*", and "Agroforest* system*" to find the foundations for an explanation of agroforestry. Table 3 provides an overview of the number of agroforestry-related scientific publications published in ScopusTM between 2000 and 2023.

In light of the aforementioned data, the findings of 85 scientific publications were reviewed and summarized.

Results

Country profile: Serbia

Serbia has a forest area of 2.3 million ha, which covers about 29.1% of its total territory and has significant potential for biomass production. The northern part of the country, Vojvodina province, is mainly a lowland agricultural region, with more than 75% of its land being cultivable [29]. This province has a very low percentage of forest cover (6.5%). The agricultural land in Vojvodina is surrounded by hedges and scattered groups of trees. The region is prone to strong winds, so windbreaks are the most common type of agroforestry systems [30].

In addition, low-intensity agroforestry systems on the banks of the Sava, Danube, Tisa, Tamiš, and other lowland rivers in Vojvodina, including semi-natural grasslands grazed by sheep and cattle in flooded forests, have been found [31]. According to Kazakova and Stefanova [31], silvopastoral systems are one of the lowland Serbia's oldest agroforestry systems. Kostić et al. [32] emphasized that special attention must be paid to the establishment of silvopastoral systems in the future as well, due to the fact that significant sections of pasture are largely on distinct saline soils. Therefore, salt-tolerant tree species yielding fruits suitable for cattle feed would mainly establish silvopastoral systems [32].

In recent literature dealing with modern trends in agroforestry, two case studies in Serbia were found. Stojanović et al. [33] applied the AgriSolar concept in agroforestry, meaning that production of wood crop short rotation of poplars and willow clones is combined with production of electrical energy through an agroforestry–photovoltaic system in a comparative study of particular designs (various solar panel types, mountings of different heights, seedling types, and different watering regimes) at the same soil conditions in Serbia for the first time. For many years, the Institute of Lowland Forestry and Environment (ILIFE), located in Novi Sad, has been researching the feasibility of creating wood biomass from fast-growing tree species such as poplars, willows, and black locust [34]. For example, the study of Pilipović et al. [35] provided valuable insights into the potential of short rotation poplar plantations for biomass-based energy production. Specifically, the mentioned study investigated the suitability of short rotation poplar plantations, particularly focusing on two commonly used clones in Serbian forestry: *Populus*×*euramericana* cl. I-214 and

Table 3 Number of published scientific papers related to agroforestry within the ScopusTM database (2000–2023)

Countries	Agroforest*	Agroforestry practice*	Agroforestry system*	Agroforest* system*
Albania	2	0	0	0
Bosnia and Herzegovina	2	0	2	1
Montenegro	0	0	0	0
North Macedonia	0	0	0	0
Serbia	10	0	5	2
Total	14	0	7	3

Last accessed: Sep. 07.2023

Note: The symbol (*) represents a wildcard used in the search query to include all variations of the root word, such as singular, plural, and derived forms (e.g., "Agroforest*" includes "Agroforest," "Agroforests," and "Agroforestry")

Populus×*euramericana* cl. "Pannonia" for biomass production intended for energy generation.

Babec et al. [36] demonstrated how to implement dynamic agroforestry in Serbia through a case study of the ot4d/ppp project. Namely, the localities examined in their study, which had been previously established with hazelnut and apple orchards, were enriched with fast, medium, and slow-growing, as well as medium and long-life cycle shrubby and wood species. These species provided shade, timber, material for soil cover production, and berry production, while field crops were grown between the rows.

According to Klašnja et al. [37], Serbia possesses significant potential for producing biomass due to its extensive forested and arable land regions. Stajić [38] also emphasizes that biomass has a substantial share of the Republic of Serbia's total energy potential within renewable energy sources. More than 60% of the total RES (renewable energy sources) potential is biomass, of which about half is wood biomass. According to Orlović et al. [34], about 80% of the wood biomass is used as firewood, while the remaining 20% represents residues from forest and industrial wood processing.

Country profile: Albania

According to the Global Forest Resources Assessment (FRA) for Albania, forests represent 36.6 percent of the land fund, while pastures and meadows cover roughly 15.6 percent, accounting for half of the land fund in the Republic of Albania [32]. Despite Albania's substantial forest cover and fertile soils, most of its forest and pastureland is in a deteriorated state. Fragile soils, combined with unsustainable forestry and agricultural activities, have resulted in significant erosion, particularly in distant highland areas where rural poverty is concentrated and persistent [40].

Agroforestry practices in Albania originate from traditional land use systems, where farmers have been using trees in their agricultural activities for millennia. This integration has been critical in addressing many demands, including timber, fuelwood, fruit production, and cattle forage [41]. Traditional agroforestry systems are ubiquitous in Albania's rural setting, where it is usual to discover multiproductive systems comprising trees, crops, and animals on tiny plots adjacent to the farmhouse [42]. According to Pisanelli et al. [41], olive trees, fruit trees, and vineyards are the most common woody components of agroforestry systems. Literature data indicates the importance of fruit trees and vineyards as a source of bioenergy production in Albania [43, 44]. Specifically, Brahushiet al. [43] emphasized that about 637.2 GWh of bioenergy can be produced annually using processing waste and pruned biomass of fruit trees, citrus trees, and grapes in Albania. Furthermore, Sulce et al. [45] stated that olive residues from the olive oil production industry are a significant alternative energy solution in Albania. On the other hand, fast-growing poplar plantations, particularly those of *Populus*×*canadensis* Moench clone I-214, hold promise for biomass production and carbon sequestration [39]. Toromani et al. [46] assessed these aspects in poplar stands of varying ages and densities.

Due to its geographical location, Albania is home to a diverse range of medicinal and aromatic plants (MAPs). MAPs are an important part of the country's non-timber forest products (NTFPs) [47]. MAPs are also a significant sector of the Albanian economy because they are the nation's primary non-timber agroforestry business [48].

Despite its advantages, Albania's agroforestry has challenges, including shifting land use patterns, rural-to-urban population migration, and farmers' insufficient comprehension of agroforestry's potential benefits. However, a recent FAO research [49] on Albanian smallholders represents a significant advancement in evidence-based decision-making that will benefit about 300,000 small farms and rural Albanian landscape. The Albanian government and other donor initiatives have collaborated to enhance access to finance for the entire agriculture sector, including small and family farms, alongside the broader economic and social development of rural areas [49]. In addition, the Albanian Local Capacity Development Foundation has collaborated extensively with agroforestry actors for many years [50].

Country profile: Bosnia and Herzegovina (BiH)

Forests are one of the Bosnia and Herzegovina's primary natural resources, representing one of the Europe's most diverse and expansive regions relative to the country's total area. According to the most recent official National Forest Inventory (NFI), forests and forest land in BiH account for 3,2 million hectares, or almost 63% of the total land area [51]. Thus, wood and related waste produced by the wood industry represent the primary source of biomass for energy production [52]. Apart from the biomass generated by the wood sector, agricultural waste also constitutes a substantial energy potential in BiH [53].

According to Cvjetković [23], agroforestry systems exist in BiH, primarily in rural regions, and have a traditional nature. Many rural inhabitants already participate in various forms of agroforestry, including the silvopastoral system, which involves raising trees and livestock on the same land. Furthermore, the sub-Mediterranean hilly-mountainous terrain around the Dinaric Alps allows for blending agrosilvopastoral and silvopastoral systems [54]. In addition, the south and south–west of BiH

are largely covered with karst terrain [31]. Despite their exceptional biodiversity, they present major obstacles to agriculture. To encourage both ecological restoration and economic growth, academics have suggested using agroforestry systems as one of the environmental restoration strategies in karst desertification zones [55].

On the other hand, considering that modern agroforestry in BiH is still in its infancy, Cvjetković [23] suggested examples of agroforestry systems that could be implemented in the Republic of Srpska. One of the initial examples is the combination of fruit trees and forest woody species, following a model from France. Additionally, a modern approach to establishing and cultivating woody species allows for planting fast-growing species like poplars in lowland areas where cereal production is the primary goal, without compromising food production. However, BiH does not have an Agroforestry Association.

Country profile: Montenegro

Montenegro's forests are an important source of natural resources. According to the FRA, Montenegro's land area has a high coverage, with forest at 59.9% and forestland at 9.9%, covering 69.8% of the land area of 1 381,200 ha. Montenegro thus ranks among Europe's three most wooded countries [56].

In rural areas, agriculture is the most important sector with 309,241 hectares (22.4% of the territory) registered as agricultural land. Most of the agricultural land is owned by family farms, accounting for 95.2%, while only 4.8% of the land is registered as agricultural holdings [57]. Thus, small-scale holdings and traditional production are features of Montenegro's agriculture. Arable agricultural land, a vital and limited resource, faces considerable strain. The comparatively small and extensively fragmented land plots significantly hinder the productivity and efficiency of smallholder farming and rural development.

Šeremešić et al. [22] stated that in Montenegro, the implementation of agroecological principles, including agroforestry as an agroecological practice, remains at a very low level. However, the number of initiatives dealing with agroforestry has increased slowly. For example, according to Beloica et al. [58], the apiculture and biodiversity of Montenegrin honey plants represent a potential for agroforestry practice in that region.

Montenegro has a substantial quantity of underused renewable energy resources, and agroforestry offers a variety of nature-based solutions. Specifically, the country has significant resources for energy production based on biomass from forestry and wood processing [59]. Biomass is the most important heating energy source in Montenegro, both in rural and urban areas. Wood biomass plays a role in Montenegro's energy balance, contributing slightly over 6% to the total energy consumption through wood combustion [60].

Montenegro also lacks an Agroforestry Association. Establishing an Agroforestry Association in Montenegro would significantly contribute to biodiversity conservation as well as sustainable agriculture. It would empower farmers, enhance environmental health, and support the country's economic development while aligning with broader sustainability goals.

Country profile: North Macedonia (NM)

North Macedonia is the 17th smallest country in Europe, a landlocked nation on the Balkan peninsula with a total size of 25,710 km^2 [20]. The territory is mostly mountainous (79%), and the rest is lowlands (19%) and natural lakes (2%) [61]. Approximately 45% of the country is classified as forest land [62], and approximately half of the territory is agricultural, with 44% being arable land and 56% being pasture land [63].

Agricultural practices are very diverse due to the specific mix of climate and topography, culture and tradition [64]. Given the prevalence of hilly pastures and meadows in rural areas, livestock rearing is a traditional practice for farmers in North Macedonia [65]. However, many pastures and meadows have disappeared in recent years due to land abandonment and the cessation of traditional farming practices [66].

As forest and agricultural land occupy a significant part of North Macedonia's territory, the potential for implementing agroforestry practices is large but unused. Furthermore, renewable energy does not constitute a significant economic aspect. Although the country has not met the set requirements, the Parliament has passed several significant laws pertaining to renewable energy sources [67].

The available data on biomass, one of the most important renewable energy sources, show that the types and regional distribution of biomass sources in North Macedonia depend on the characteristics of individual regions. Biomass is primarily available in the country's agricultural and forest regions. Wood and charcoal account for approximately 80% of the total biomass used for energy purposes. The capacity for energy generation from biogas has not been sufficiently explored [68].

North Macedonia does not have an Agroforestry Association. However, agroforestry development in North Macedonia can significantly contribute to sustainable development, improve farmers' economic stability, and preserve natural resources. With the support of research institutions and the application of innovative practices, the country can maximize its potential.

Strategies for strengthening agroforestry systems as a potential for energy production from forest biomass

Despite the potential and significant challenges the Western Balkan countries face in transitioning to renewable energy, agroforestry still lacks the attention it deserves. This is due to the prevailing separation between land use management in forestry, agriculture, and energy. To overcome these barriers, agroforestry sector development programs must consider the roles played by every component and supporting function within the supply chain. In countries where the forest sector plays an important role, such as in the case of the WB countries, the function and effectiveness of the following elements determine the strength of the forest sector [69] as well as the robustness of the agroforestry sector: (1) a legislative framework; (2) a skilled workforce; (3) private forest owners' associations; (4) restructuring the public enterprises; and (5) research institutions.

A significant disparity exists between the current availability of agroforestry resources and their potential, as opposed to their actual usage. Consequently, the study proposed a novel concept for an initiative to enhance the agroforestry, agriculture, and energy nexus. This initiative must address all elements depicted in Fig. 2.

This figure depicts a diagram in which the orientation of arrows indicates the interconnectedness of various sectors and functions within the agroforestry system. Agroforestry, positioned at the center of the diagram, is the key concept of this model. Agroforestry integrates the two principal sectors, agriculture and forestry, within public and private endeavors. Agriculture is directly linked to the agriculture research function, while forestry, on the other hand, is connected to the forestry research function. These research functions, along with human resources, form the foundation for supporting agroforestry development. The diagram suggests that agroforestry does not operate in isolation but in synergy with different sectors. It highlights that both the energy sector and the circular economy principles are associated with agroforestry through agriculture, forestry, a supportive legislative framework, and human resources. Energy and the circular economy are integral to sustainable development and resource management within the agroforestry systems. At the same time, feedback loops indicate that agroforestry contributes to sustainable energy production. This diagram clearly illustrates the complex network of interactions necessary for the sustainable and efficient functioning of the agroforestry system.

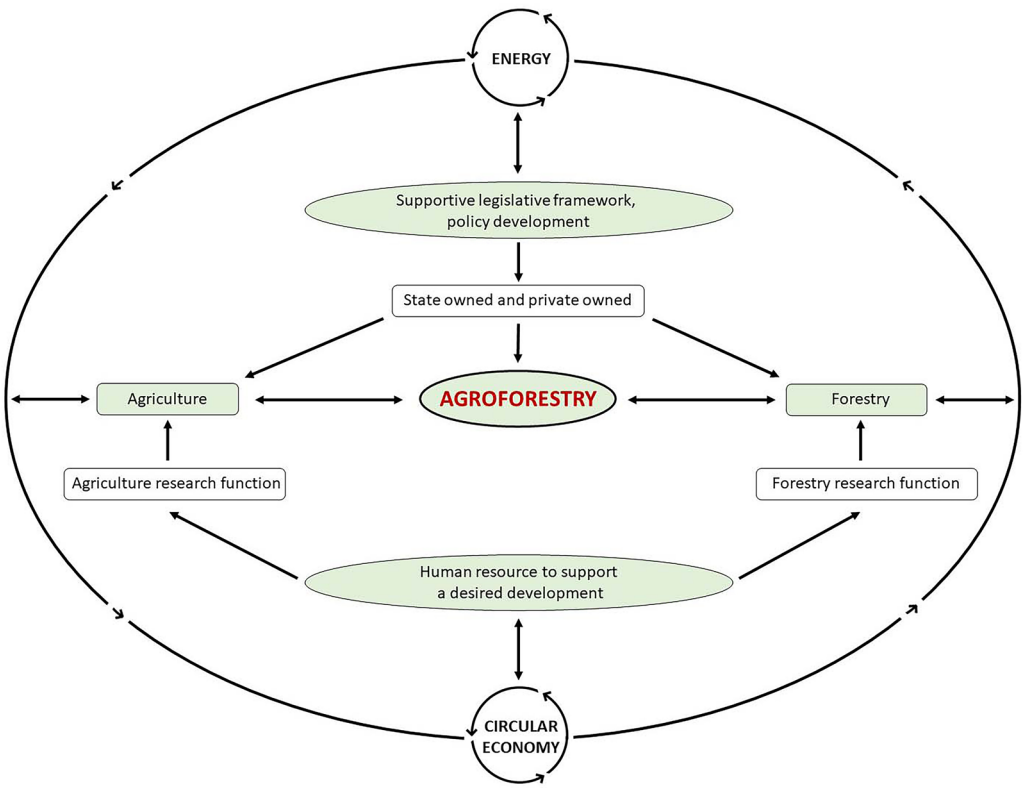

Fig. 2 Supply chain and main elements of the agroforestry–agriculture–energy nexus (Source: Authors)

Table 4 Agroforestry, agriculture, and energy nexus: problem solution matrix

Problem	Solution
Legislation separating agricultural and forest land, without recognizing agroforestry—all WB countries	1. Make agroforestry visible o Defining and adopting legal frameworks to support agroforestry, along with developing guidelines for implementation
Lack of knowledge and cooperation among key stakeholders—all WB countries	1. Encouraging land users at all levels o Aim: to recognize agroforestry as a dynamic system that sustains and divides output while providing social, economic, and environmental benefits 2. Provide a training program and set of instructions to assist farmers in creating business strategies that are connected to value chain development in order to establish and oversee agroforestry systems in various geographic areas
High energy demands—all WB countries	1. Energy plantations o In this system, trees are grown to meet the energy demands of the rural masses
Climate changes and their negative impact on the WB countries	1. Agroforestry systems o Play a significant role in sequestering carbon and contributing to climate change mitigation; o Transition from fossil fuels to renewable energy sources offered by agroforestry
In Serbia, agroforestry lacks sufficient visibility	Legislative solutions: 1. Policy integration: o Solution: Integrate agroforestry into national agricultural and environmental policies 2. Financial incentives: o Solution: Provide financial incentives for farmers to adopt agroforestry practices 3. Land tenure security: o Solution: Ensure secure land tenure for farmers practicing agroforestry 4. Environmental regulations: o Solution: Promote agroforestry as a tool for environmental conservation Practical solutions: 1. Education and training: o Solution: Enhance farmers' knowledge and skills in agroforestry 2. Research and development: o Solution: Invest in research to identify best practices and suitable species for agroforestry in Serbia 3. Pilot projects and demonstration farms: o Solution: Establish pilot projects and demonstration farms to showcase agroforestry benefits
Despite its advantages, Albania's agroforestry has challenges, including shifting land use patterns, rural-to-urban population migration, and farmers' insufficient comprehension of agroforestry's potential benefits	1. Incentivizing agroforestry adoption Solution: Financial incentives and subsidies 2. Education and training programs Solution: Extension services and training workshops 3. Promoting agroforestry through policy support Solution: Supportive policies and regulatory frameworks 4. Addressing rural-to-urban migration Solution: Enhancing rural livelihoods and infrastructure 5. Demonstrating economic viability Solution: Showcasing successful agroforestry models 6. Creating market access Solution: Developing value chains for agroforestry products 7. Community engagement and participation Solution: Encouraging local community involvement

Table 4 (continued)

Problem	Solution
Modern agroforestry in BiH is still in its infancy	1. Silvoarable systems (Alley cropping): • Example: Plant walnut trees in rows with crops like wheat or vegetables in between • Benefits: Provides nuts, timber, and improved soil fertility 2. Silvopasture (forest grazing): • Example: Graze sheep or goats in managed forest areas • Benefits: Offers natural forage for livestock and reduces undergrowth, lowering fire risk 3. Forest farming: • Example: Grow medicinal plants like ginseng or mushrooms under the forest canopy • Benefits: Diversifies income and maintains forest health 4. Riparian buffers: • Example: Plant native trees like willows along riverbanks • Benefits: Protects water quality and stabilizes banks 5. Woodlots and biomass production: • Example: Establish short rotation coppicing with poplar or willow • Benefits: Provides renewable energy and reduces pressure on natural forests 6. Windbreaks and shelterbelts: • Example: Plant rows of trees such as pine along crop fields • Benefits: Protects crops from wind damage and reduces soil erosion
High forest cover and diverse ecological conditions, but scarce arable land in Montenegro	1 Redesigned land parcels for more efficiency and addressing land abandonment o Agroforestry redesigns land parcels for enhanced efficiency by boosting productivity, providing essential ecosystem services, and making land more resilient to climate change. It also addresses land abandonment by restoring degraded lands and offering diversified income opportunities, thereby revitalizing rural economies and communities 2 Consider the benefits of large forest cover of the territory in the context of tree energy via agroforestry o In Montenegro, where forest cover is significant, agroforestry can play a crucial role in enhancing energy security, promoting sustainable land use, and supporting local economies by integrating tree-based energy solutions
In recent years, the biggest threat to North Macedonia's agricultural landscape diversity has been the significant loss of pastures and meadows due to land abandonment and the cessation of traditional farming practices	1. Restoration of abandoned lands and biodiversity enhancement o Agroforestry can rejuvenate abandoned lands by reintroducing productive activities. Planting trees, shrubs, and other perennial plants can improve soil health (by reducing erosion, enhancing soil organic matter, and improving nutrient cycling), increase biodiversity, and make these lands productive again 2. Economic benefits: o Agroforestry provides multiple income streams by diversifying the types of crops and products that can be harvested (e.g., fruits, nuts, timber, and forage). This can make farming more economically viable and attractive, potentially reversing land abandonment trends 3. Support for Traditional Practices: o Agroforestry can integrate and support traditional farming practices, such as silvopasture. Additionally, it can contribute to preserving North Macedonia's valued traditional landscapes In North Macedonia, promoting agroforestry could be a strategic approach to revitalizing agricultural landscapes, enhancing biodiversity, and supporting sustainable development in rural areas

To enhance the visibility of agroforestry, it is first necessary to investigate policy changes that should incorporate agroforestry primarily through the forestry and agriculture sectors. Integrating policy decisions across sectors can bridge the historical divide between forestry and agriculture. Additionally, both state and private institutions should consider increasing funding for agroforestry programs. It is also important to ensure that policy instruments and investments that place small-scale farmers at the forefront are in place. This includes clarifying tree rights, land rights, and carbon rights, which are fundamental for implementing agroforestry practices. Key stakeholders need to share lessons learned from agroforestry practices and projects. Incorporating

the principles of the circular economy into agroforestry initiatives is essential for promoting sustainable development and resource efficiency. The circular economy, which aims for 'zero waste' by transforming 'waste' into 'resources', provides a framework that complements agroforestry's goals by fostering sustainability and reducing environmental impact. By adopting these principles, agroforestry can significantly contribute to the region's sustainable development and resource efficiency [70]. To achieve a positive impact on agroforestry, human resources should support research and development in the circular economy, agriculture, and forestry, focusing on socioeconomic aspects and long-term effects. Thus, the bioenergy–circular economy–agroforestry nexus supports sustainable development by promoting efficient resource use, reducing greenhouse gas emissions, and enhancing energy security. Agroforestry's contribution to bioenergy production creates a feedback loop where energy generation aligns with ecological conservation and economic resilience.

The study's findings suggest using problem solution matrix analysis to support the targeted issues (Table 4).

Conclusions

The potential for agroforestry in the WB countries is high yet untapped, primarily due to the lack of knowledge about the establishment, contemporary management and sustainable application of agroforestry systems, as well as the ambiguous status of agroforestry under legislation. Energy dependence of all WB countries is at a high and unfavorable level; therefore, any advancements in the transition to sustainable energy sources must be approached with careful consideration. Agroforestry offers a perspective for creating sustainable energy systems that reduce dependence on fossil fuels and mitigate climate change. Energy imports will be reduced, and stable and ecologically sustainable sources of energy will be provided, while maintaining the stability of agricultural and water resources. The research summarized findings from scientific research across five WB nations and proposed incorporating agroforestry systems into the region's comprehensive sustainable development framework. This is particularly significant due to the immense potential for acquiring biomass. Specifically, all WB countries have significant forest potential. Agroforestry has been recognized as a concept since ancient times and has been implemented in certain rural regions; however, its impact on sustainable energy development at the national and regional levels is negligible. The primary cause is the absence of a strategic approach by the states to this issue: there is no education or advocacy for agroforestry specifically targeted at the population, and agroforestry is not recognized within the current legislative framework or sustainable development strategies. Agriculture and forestry are two distinct sectors that are subject to the creation of separate development plans and are supervised by various institutions within the system. Their integration into the agroforestry system exists only as a scientific concept.

In light of the research findings, it is evident that the development of novel models, intersectoral collaboration, and interstate cooperation are essential priority areas for future research, with an emphasis on the need to use natural resources in a sustainable manner. Forest resources hold significant biomass potential, yet their usage is either insufficient or unsustainable. Therefore, it is imperative to conduct comprehensive reforms that commence with implementing novel public policies and conclude with the tangible implementation of energy production from forest biomass. It is impossible to predict the extent to which it will be possible in the period of intricate geopolitical changes that transpired after 2022. Nevertheless, the agroforestry–agriculture–energy nexus model of development must be further researched and promoted, taking into account the vast natural potential that the WB countries have at their disposal, as well as the challenges associated with ensuring sufficient energy supply and further development through the implementation of sustainable practices.

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Author contributions

M.B. prepared the concept of the study, prepared literature review and data processing. I.V. made paper structure, analysis and proposed a novel concept to enhance the agroforestry, agriculture, and energy nexus. Z.M. takes part in preparation of the manuscript draft. All authors participated in manuscript editing and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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