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"Waste to energy" as a driver towards a sustainable and circular energy future for the Balkan countries

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Abstract

Background The main goal of the paper is to review the existing state and propose a model solution for the introduction of the waste-to-energy concept in the Republic of Serbia and Bosnia and Herzegovina, as these Balkan countries are a source of high pollution due to the inefficient use of fossil fuels and the operation of coal-fired power plants. Besides, these countries have very low level of waste management, which results in the uncontrolled disposal of a large amount of waste which consists of plastic and microplastic materials which are difficult to decompose in natural ecosystems.

Methods Considering the type and objectives of the study, a mixed research method was chosen as a combination of exploratory research, descriptive research, explanatory research, and modeling.

Results The main result of the research shows the unfavorable situation in the field of waste management in the Republic of Serbia, as well as in Bosnia and Herzegovina. Both countries have adopted adequate strategies and plans, but waste management is not implemented accordingly, Nevertheless, numerous problems create considerable opportunities for improvement, especially regarding the potential for energy production from waste, which is an important approach to implementing the circular economy model. The study showed that the situation is particularly unfavorable in rural areas. Hence, the research proposes (a) a novel model for waste-to-energy governance and (b) a novel model for waste-to-energy management in rural areas. The research was done, and models were developed based on the examples of the Republic of Serbia, and Bosnia and Herzegovina. However, the results can be used in countries with a similar level of waste management and with a larger share of rural areas.

Conclusions The paper emphasizes the importance of a holistic and systemic approach to waste management, with emphasis on using waste-to-energy concept as particularly applicable in the transition to circular economy. This study proposes a model for the integration of waste management (with emphasis on plastic and microplastic) and energy efficiency, presenting a model of approach that can be used in countries that are at the beginning of introducing a circular economy.

Keywords Waste to energy, Circular economy, Policy and governance, Plastic and microplastic waste, Bosnia and Herzegovina, Republic of Serbia

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Introduction

In September 2015, the United Nations General Assembly adopted the 2030 Agenda. It contains 17 Sustainable Development Goals (SDGs), which establish measurable targets in the social and economic elements of sustainable development and in the field of environmental protection. The attainment of all 17 sustainable development goals by 2030 is a prerequisite stipulated in the 2030 Agenda [1]. While there is no explicit sustainable development goal pertaining to waste, several goals and targets of sustainable development are associated with waste, both directly and indirectly [2]. Sustainable development goals are not legally binding. However, they have found their place in the development strategies of many countries, with the countries of the European Union certainly clearly leading the way. The European Green Deal establishes the primary goals of the European Union's sustainable development, with the transition from a linear to a circular economy and the decarbonization of Europe by 2050 as the top priorities. Waste management is one of the fundamental problems for which the circular economy concept offers a wide range of solutions, and one of the most acceptable is the application of the "waste-to-energy" (WtE) approach, which solves the problem of waste and produces energy that does not require the use of fossil fuels [3].

If waste is not handled adequately, it poses a risk to human health and the environment [4]. Waste management is one of the key issues of sustainable development, especially if one considers the variety of waste and its potentially harmful effects, as well as the limited capacities of developing countries and economies in transition. Based on the preceding, it is feasible to deduce that waste management is intricately linked to a number of additional worldwide predicaments, including but not limited to health concerns, climate change mitigation, reduction of poverty, natural resource and food security, and sustainable production and consumption [5].

The 2030 Agenda is generally committed to reducing the negative impacts of urban activities and chemicals hazardous to human health and the environment through proper management and safe use of chemicals, waste reduction and recycling, and more efficient water and energy use. By analyzing the sustainable development goals of the 2030 Agenda, it is possible to conclude that six of the 17 sustainable development goals, which promote human well-being, take into account sustainable waste management. Nonetheless, nearly all of the objectives of sustainable development can be linked to waste if waste is regarded not only as a matter of significance for environmental preservation, but also as an economic and social concern, embodying sustainable waste management. For example, achieving Goal 12—"Ensure sustainable consumption and production patterns"—is impossible without proper waste management because unsustainable patterns of consumption and production increase waste generation and pressure on the environment, as well as on social and economic aspects.

To implement the 2030 Agenda, the UN and other international organizations have proposed specific waste management indicators for specific goals. Each country should adapt them to its national goals, i.e., include them in national planning processes, policies, and strategies, taking into account the circular approach [6].

Municipal waste management includes the collection, treatment, and final disposal of waste produced by households, small and medium-sized enterprises, medical institutions, shops, craft shops, industry, agriculture, etc. The current linear economic model based on the "take–make–dispose" pattern is reaching its physical limits amid estimates that the waste produced annually will reach 2.59 billion tons by 2030 and that this amount will rise to 3.40 billion tons worldwide by 2050 [7].

The traditional linear production process ("take–make–dispose") tends to be replaced by a circular production process: circular economy (CE). As a fundamental part of CE, the service life of materials is extended through the imperatives of reduction, reuse, recycling, and recovery, which are widely accepted as the foundations of CE [8]. In other words, materials and resources must be kept active in the economy for as long as possible by extending their lifespan, thereby minimizing waste. Recycling is one of the ways to reuse products and thus reduce the extraction of primary natural resources [9].

Waste management in the European Union (EU), towards CE, represents a key challenge for achieving the goals of sustainable development. Accordingly, the EU has established a series of legal frameworks that determine the responsibilities of all participants in the waste management chain. One of the key documents is the Waste Framework Directive 2008/98/EC (WFD) [10], which establishes objectives for reducing the amount of waste disposed of in landfills, increasing recycling and reuse of waste, and promoting the use of waste as a resource. On the other hand, the CE Strategy (COM/2015/0614) [11] upholds the concept of waste management based on the waste hierarchy as a way to achieve the best overall environmental outcome and to return valuable materials to the economy. The aim of the European Strategy for Plastics in a Circular Economy (COM/2018/028) [12], according to the 2030 program, is to ensure that all plastic packaging is recycled. The strategy encourages a circular approach that favors the use of sustainable and non-toxic reusable products over single-use plastic products. This strategic document also sets special requirements in terms of a complete ban on

the production and marketing of certain products, reduction of waste generation, development of the plastic waste management system, and prevention of pollution. A New EU Action Plan for a cleaner and more competitive Europe (COM/2020/98) [13], adopted in 2020, prescribes ambitious measures to stimulate the transition to CE, i.e., to develop an efficient and competitive economy to ensure zero greenhouse gas emissions at the EU level by 2050. The focus of the measures in this waste management action plan is directed towards the complete avoidance of waste generation, i.e., its transformation into high-quality secondary raw materials, as well as towards the good functioning of the secondary raw materials market and the fight against illegal shipments.

Adaptation of economic systems and transition from linear economy to CE is the obligation of all countries in order to contribute to the achievement of sustainable development promoted by the EU. In heading towards CE and sustainable development, obstacles arising from an insufficiently coordinated legislative framework and policies to encourage CE, a lack of infrastructure to increase the use of valuable secondary raw materials and reduce waste disposal, and insufficient public information about the advantages of CE and a sustainable waste management system must be overcome [14]. CE is a new way of creating value and, ultimately, of prosperity. It functions by extending the service life of products through improved design and servicing and by moving waste from the end to the beginning of the supply chain. Specifically, it allows more efficient use of resources that are utilized repeatedly rather than just once [15]. CE is closely related to sustainable development, that is, to the United Nations' sustainable development goals, including Goal 12: Sustainable consumption and production [16].

By keeping products, components, and parts in their use and maintaining their maximum value at all times, CE is based on the efficient use of our natural resources while reducing environmental impact. By creating industrial systems that are regenerative in nature, CE simultaneously reduces resource dependence and minimizes waste production. In addition to the direct cost savings associated with resource extraction and waste processing, CE increases supply chain resilience and reduces greenhouse gas emissions while increasing the potential for innovation and job creation [17, 18].

CE is transformative as it signifies a cultural shift towards alternative methods of production and consumption, introducing new models for business and management practices. It requires a holistic and systemic approach that cuts across sectoral policies and a functional approach that goes beyond the administrative boundaries of cities in order to close narrow and slow loops [19, 20]. Waste generation is minimized in CE with the help of careful design of new products and industrial process in which materials are continuously circulated in a closed loop [21]. Application of the CE concept encourages environmental protection and social well-being [22].

In developing countries, CE can have a significant impact on reducing poverty and increasing productivity and sustainable development. However, the implementation of CE in developing countries faces a number of challenges. Many of these countries are characterized by limited resources, poorly developed infrastructures, and a lack of financial means to invest in new technologies. In addition, it is important to take into account cultural and social factors that can affect the success of implementation. With the right approach and support, CE can be a key element in the development of developing countries, in reducing poverty, stimulating economic growth, and protecting the environment.

Efforts to implement CE in waste management have been recognized in EU member states and beyond. Many examples speak in favor of this fact. Progress is noticeable through the implementation of public policies at the national level as well as through individual initiatives in the industrial and economic sectors. The countries of Western Europe, Japan, and China are recognized as leaders in encouraging the CE model, and their governments have played a key role in providing incentives and supporting companies to adopt circular business models [23].

In order to prolong the life of the products and avoid waste production, as well as the use of energy and natural resources required to create new products, Austria introduced Eco-Vouchers in 2022 for the repair services of electrical and electronic devices that are most frequently used in households [24]. In Scotland, major construction companies use pelletized recycled plastic to replace petroleum tar from bitumen and use it in road construction [25]. The "Plastic Pact", in force in the Netherlands, is an agreement between the Dutch government and over 100 companies that use or produce plastic. The agreement was established with the aim of placing fully recyclable plastic on the Dutch market and encouraging its reuse wherever possible and feasible. Also, the agreement stipulates that 20% less plastic is used in producing disposable packaging [26]. In 2021, Denmark achieved a 93% return on single-use packaging through the implementation of a deposit system for used and returned packaging, recycling 1.9 billion cans and bottles for reuse. The application of this system increases the recycling rate of packaging waste, supports the circular approach, and significantly contributes to the EU goal of collecting 90% of plastic bottles by 2029 [27].

China has developed a wide range of activities to realize the CE concept and implemented a comprehensive

policy for the application of CE. In 2020, China set a goal of achieving carbon neutrality by 2060. The emphasis is on new business models, the industrial symbiosis of cities through the application of material flow analysis, and the reduction of CO_2 emissions [28]. The Japanese food industry recycles about 85% of food waste, turning it into animal feed, fertilizer, or methane [29].

In the US, many organizations, including for-profit companies, social enterprises, non-profits, and government organizations, are taking concrete measures to promote the principles of the circular economy. Consider the materials management industry, which uses waste as a resource in most of its business models. Companies that deal with waste management from the commercial and industrial sectors, including organic waste, as well as recycling materials, including plastic, steel, batteries, etc., are responsible for 32% of initiatives that promote the use of waste as a resource throughout America. Organizations develop innovations in the fields of plastic recycling technologies (BioCellection, Purecycle), preventing textile waste from being dumped in landfills (FabScrap, CarpetCycle), and creating online platforms to encourage the exchange of materials and by-products on the American market (US Materials Marketplace) [30].

The implementation of circular economy ideas in South Australia is mostly focused on changing the way the economy values and utilizes resources. This is achieved through using and recycling waste from households, developing industrial solutions to reduce food waste, transforming packaging and single-use items, etc. In this regard, in 2019, the Government of South Australia initiated a research consortium to convert large amounts of waste from primary agricultural production into high-quality products such as cosmetics, pharmaceuticals, or packaging [31].

Today, modern society is faced with large amounts of waste. Waste is created as a consequence of all human activities. Unsustainable patterns of production and consumption of natural resources contribute to the generation of an increasing amount of waste, and inadequate disposal of waste leads to the loss of valuable components from waste and incalculable consequences for the environment and human health.

According to data presented in the 2018 European Strategy for Plastics in a Circular Economy, 25.8 million tons of plastic waste are generated in Europe every year, of which less than 30% is collected for recycling. Additionally, the strategy identifies microplastics as a special problem, which, in European countries, are emitted into the environment in quantities of 75,000 to 300,000 tons per year. Plastic microparticles (less than 5 mm) enter the environment through the fragmentation of plastic waste and direct emission, given that they are used as additives in many production processes, which makes it challenging to monitor and control their emission into the environment [32].

The classification of waste in EU member states is carried out according to the Waste Catalogue (EWG), which has been transposed into the legislation of the Republic of Serbia and Bosnia and Herzegovina. Within the Catalogue, waste is systematized according to the activities in which it was generated but also according to the type of waste, materials, or processes [33].

Waste can be classified according to its essential characteristics, taking into account different criteria. Depending on the source of origin, waste is divided into municipal waste, solid waste that is generated in urban areas and is mostly household waste and commercial waste; industrial waste, i.e., waste material created during the industrial process, and according to its characteristics can be hazardous or non-hazardous; waste from health institutions (medical waste), i.e., all waste generated in health institutions, regardless of its composition, characteristics and origin; construction waste, includes excavated soil, demolition and construction waste (waste ceramics, concrete, iron, steel, plastic, etc.) and waste asphalt and concrete; agricultural waste—resulting from residues from agriculture, forestry, food and wood industry, etc. [34].

Waste can be inert, non-hazardous, and hazardous depending on the hazardous characteristics that affect human health and the environment [35]. Special waste streams to which the principle of extended responsible producer applies include waste tires; spent batteries and accumulators; waste oils; waste from electrical and electronic equipment; waste fluorescent tubes containing mercury; waste containing asbestos; packaging waste; waste that contains, consists of or is contaminated with persistent organic pollutants (POPs waste); medical and pharmaceutical waste; by-products of animal origin; agricultural waste; sludge from municipal wastewater treatment plants; construction and demolition waste; mining waste; waste from titanium-dioxide production; secondary waste from waste treatment [36].

According to data from 2020, only about 35% of plastic waste is recycled, with the remaining 65% going toward energy use or disposal. This is despite the fact that member states of the European Union have very extensive strategic, planning, and legal frameworks for the implementation of a circular approach in the management of waste in general, including waste plastics [37]. This approach is opposed to the concept of a circular economy, taking into account the ambitious goals of the European Union on the complete recycling of generated packaging waste, including plastic packaging waste. Although the rate of plastic recycling

at the level of the European Union increased by 15% compared to 2018, reaching 4.6 million tons [38], the progress is still insufficient to meet the various industrial targets, and additional efforts are needed to reach the total circularity of plastics and plastic waste.

The subject of the research in this paper is an overview of the state of municipal waste management in Bosnia and Herzegovina (BIH) and the Republic of Serbia (Serbia). The aim of the paper is to highlight the advantages and disadvantages in this sector and propose measures for policy-making and governance novelties and improvement in current waste management in order to implement CE in full scope in these two countries in the future.

Methods

The selection of research methods is primarily determined based on the fact that waste management and its use for obtaining energy are problems regulated in Western Balkan countries exclusively by specific legal provisions and related rules. In addition, scientifically based research and studies are rare, and the amount of available data are insufficient to conduct data analysis that could be considered acceptable regarding statistical reliability. Therefore, a mixed research method was chosen.

First, it was determined that the exploratory research approach was appropriate for investigating subjects for which there is not enough reliable data and for which it is necessary to form a specific basis for the research process.

Descriptive analysis was chosen because it is based on the description of the observed phenomenon (waste management, energy production from waste), for which the input information was obtained by applying the previously performed exploratory analysis.

In order to fill the gaps that evidently exist when it comes to the observed research problem, the explanatory research method was selected and applied to the results obtained by applying exploratory and descriptive analysis.

In consideration of the imperative to enhance waste management practices in the Western Balkans and promote the adoption of the "waste-to-energy" methodology, the concluding section of the research utilizes modeling as a distinct research technique that facilitates the development of a more comprehensive waste management system and an overview of its components and interrelationships. Thus, a proposal is presented to support further research on the particulars of the Western Balkan countries.

Results

Waste management in Bosnia and Herzegovina

BIH is a country in Southeast Europe. It covers an area of 51,222 km^2 with 3,531,159 inhabitants. As for the population of Bosnia and Herzegovina, 43% is urban, and 57% is rural [39]. BIH consists of two entities: The Federation of Bosnia and Herzegovina and Republika Srpska, and the Brčko District of Bosnia and Herzegovina. Waste management is entrusted to entities and to the Brčko District.

Amount and composition of waste in BIH

The amount of waste depends on economic conditions, standard of living, urbanization, and the population [40]. Municipal waste production per inhabitant ranged from 0.09 kg/day in Ghana to 5.50 kg/day in Antigua and Barbuda; the median was 0.94 kg/day [41]. In 2021, the amount of municipal waste collected in BIH amounted to 1.23 million tons, i.e., 0.98 kg per inhabitant per day [42]. The amount of municipal waste per inhabitant in BIH in the period from 2018 to 2021 ranged from 0.97 to 0.98 kg/day (Table 1).

The characteristics and composition of municipal waste depend on the topography of the area, season, eating habits, living standards of the population, type of residence (apartment buildings or houses), etc. [43]. The composition of waste in BIH was analyzed at the entity level, Republika Srpska and the Federation of Bosnia and Herzegovina and the Brčko District. The composition of municipal waste generally differs depending on the entity, region, and other factors (Table 2). The dominant fraction of municipal waste in BIH is biodegradable waste (kitchen waste, fruit and vegetable waste, garden waste, etc.), which makes up to 56% of municipal waste. In countries with low and medium levels of development, biodegradable waste constitutes 46–53% of municipal waste, and this percentage stands at 34% in highly developed countries [44]. Fractions of waste that can be recycled—such as plastic, metal, glass, paper, and cardboard, make up more than one-third of municipal waste in BIH [45–47]:

Municipal companies carry out waste collection in Bosnia and Herzegovina. The majority of citizens dispose of municipal waste in containers with a volume of 1100 L [48]. The equipment of utility companies is outdated, while some parts of the equipment are decades old, and

Table 1 Amount of municipal waste in BIH (2018–2021)

Year	2018	2019	2020	2021
Amount of waste (million tons)	1.24	1.23	1.21	1.23
Median daily amount of waste per inhabitant (kg)	0.97	0.98	0.97	0.98

Table 2 Composition of municipal waste in Republika Srpska, the Federation of Bosnia and Herzegovina and the Brčko District (%)

	Republic of Srpska	Federation of Bosnia and Herzegovina	Brčko District
Organic waste	40.30	15.00–56.09	26.00
Wood	2.83	< 7.32	8.86
Paper and cardboard	14.66	7.54–17.00	11.54
Plastic	16.36	5.00–14.95	8.36
Glass	4.43	2.5–9.34	5.85
Textile	3.84	< 9.52	9.28
Metal	3.66	< 1.21	1.73
Other	13.92	–	28.38

Collection and transport of municipal waste in BIH

more than half of the trucks are vehicles that were not purchased new, but already used.

Regions in countries with low levels of development tend to have low efficiency of charging for utility services. The charge efficiency rate varies in developing countries, with bigger cities reaching greater rates and smaller cities obtaining significantly lower rates. Municipal waste management policies in developing countries primarily focus on the timely removal of waste from densely populated areas in order to maintain hygiene and health. On the other hand, residents of sparsely populated areas frequently construct illegal landfills because municipal waste collection services are not always available in these areas due to limited municipal budgets.

Although there is no complete data, it is estimated that around 75% of citizens and businesses have organized waste collection. The highest percentage (about 85%) refers to urban areas, while waste collection is organized only in 42% of rural areas.

Waste treatment and disposal in BIH

Municipal waste treatment options can be broadly classified as landfilling, incineration, recycling, and composting. Sustainable waste management is one of the most challenging issues in both developed and developing countries that are now trying to cope with pressure from the national and international community to reduce the overall environmental impact. An important driver of this concept is the waste hierarchy. It gives top priority to preventing waste in the first place. Even when waste is finally generated, priority is given to its preparation for reuse, then to recycling, recovery, and, as a last resort, landfilling [49].

In the EU in 2020, 39.2% of waste was recycled, and 32.2% was landfilled [28]. In 2019, Germany was the leading country in recycling, with 67% of municipal waste recycled or composted. While eight Member States (Germany, Sweden, Denmark, Finland, the Netherlands, Luxembourg, Austria, Belgium) landfilled less than 10% of their waste—the target set by the new Landfill Directive for 2035—ten Member States still landfill more than 50% of all municipal waste (Hungary, Slovakia, Spain, Latvia, Bulgaria, Croatia, Greece, Romania, Cyprus, Malta) [50].

Landfill management in BIH is the responsibility of utility companies. Currently, 84 municipal landfills do not meet most of the basic sanitary criteria [51]. Apart from official municipal landfills, there are also many illegal landfills (about 1400) [52]. The use of regional landfills by municipalities is modest. Namely, only a third of the 142 municipalities use regional landfills, nine of which are in the entire country. Based on that, it is concluded that about 47% of the population of BIH is covered by regional landfills [30]. Some municipalities abandoned the regional concept due to high transport costs and additional fees for waste disposal [53].

The rate of secondary raw material separation and waste recycling stands at 14%. Organic waste is not separated because there is no demand for compost, so it is disposed of in a landfill.

Eight utility companies have installed waste sorting lines (Mostar, Konjic, Sarajevo, Tuzla, Čapljina, Bihać, Banja Luka, and Doboj), most of which are not in operation due to financial sustainability issues. There are no other technologies for (pre)treatment of municipal waste. Two cement factories use RDF/SRF as an alternative fuel.

Waste management in Serbia

Serbia is a country in Southeast Europe, covering 88,499 km^2 with 6,834,326 inhabitants, of which 57% are urban residents and 43% are rural residents. Waste management in Serbia is a complex process that involves various participants, and their responsibilities are determined by the legal framework. At the state level, the Ministry of Environmental Protection is responsible for waste management, and it has the authority to develop and implement national strategies and plans for waste management, harmonize legal frameworks with European norms, coordinate between different sectors, and encourage the development of new technologies and innovations in waste management. At the local level, waste management is the responsibility of local self-government units, which are in charge of the organization and implementation of the waste collection, transportation, processing, and disposal systems. Local self-government units are also responsible for conducting campaigns to raise awareness of the importance of waste separation and recycling and for enforcing penalties for illegal dumping.

Table 3 Amount of municipal waste in Serbia (2018–2021)

Year	2018	2019	2020	2021
Amount of waste (million tons)	2.80	2.83	2.95	2.87
Median daily amount of waste per inhabitant (kg)	1.10	1.11	1.15	1.14

Table 4 Composition of municipal waste in Serbia

	Republic of Serbia
Organic waste	40.00
Wood	3.40
Paper and cardboard	13.00
Plastic	12.10
Glass	4.10
Textile	2.80
Metal	5.20
Other	19.40

Collection and transport of waste in Serbia

Amount and composition of waste in Serbia

In 2021, 2.87 million tons of municipal waste were generated on the territory of Serbia, and the median daily amount of municipal waste per inhabitant was 1.14 kg (Table 3) [54]. The average amount of waste generated by a citizen of Serbia in 2021 was about 416 kg, far less than that of citizens in the EU (530 kg of municipal waste per capita were generated in the EU in 2021) [55]. In 2018, when 2.80 million tons of municipal waste was generated, the amount of waste increased by 2.5% [56].

The dominant fraction of municipal waste in Serbia is biodegradable waste (waste from the kitchen, remains of fruits and vegetables, gardens, etc.), which makes up about 40%. Glass makes up 4.1%, paper and cardboard 13%, plastic (PET, bags, etc.) 12.1%, metal 5.2%, and 25.6% other (textile, wood, leather, ash, etc.). One-third of waste in Serbia consists of recyclable raw materials (paper, cardboard, metal, and plastic). The data are presented in Table 4 [57].

As in Bosnia and Herzegovina, the initial problem in the analysis in Serbia is incomplete data. Citizens in Serbia usually have 1100-L containers available for waste disposal. There is no reliable data, but it is evident that during the last five years, underground containers with a volume of 3000–5000 L have been used in major cities in areas with high population density. In rural areas, containers with a significantly smaller volume or special bags are used.

Organized waste removal exists in urban areas, but in rural areas, it is significantly less organized or nonexistent. The average scope of waste collection is 88%. Rural parts of Serbia are not covered by the waste collection service, and that waste ends up in illegal landfills.

There are recycling facilities in only eight cities in Serbia. It is obvious that they are not only associated with the largest cities, and it is reasonable to assume that local initiatives can significantly impact the aforementioned. Hazardous waste management is at a very low level, with restrictive access to data.

Municipal companies that deal with waste removal work with outdated equipment that is often not specialized but is used for different needs, and the logistics management system is at a low level or does not exist. [58].

Waste treatment and disposal in Serbia

In Serbia, 12 regional sanitary landfills were built by 2021 (Užice, Lapovo, Kikinda, Jagodina, Leskovac, Pirot, Sremska Mitrovica, Pančevo, Vranje, Gornji Milanovac, Subotica and Belgrade), and two are in the construction phase (Nova Varoš and Inđija). The National Waste Management Strategy envisages 29 regional sanitary landfills with waste separation centers and transfer stations. Apart from sanitary landfills, there are 135 unsanitary landfills on the territory of Serbia, and waste is still disposed of in 85% of them. In addition to sanitary and unsanitary landfills, 2656 illegal landfills were registered. In most cases, illegal landfills are located in rural areas due to the lack of funding to expand the waste collection system and the insufficient organization of waste management at the local level.

The latest available data for 2020 show that only 18% of municipal waste is disposed of in sanitary landfills. Of the 2.87 million tons of municipal waste generated in 2021, 2.48 million tons, or 86%, were disposed of in landfills. The amount of 390,000 tons of waste, or 14% of the collected waste, was subjected to the reuse process, and the most common materials in the processing were metal, paper, and cardboard. The infrastructure for separate waste collection is not sufficiently developed in relation to existing recycling capacities, while there are several registered facilities for recycling PET and other types of plastic, metal, paper, etc.

Although municipal waste contains a high degree of organic waste, there is no network for the separate collection of this fraction of waste, nor are there facilities for the biological treatment of municipal waste, except in the Regional Waste Management Center in Subotica. Serbia does not have the necessary infrastructure to reduce the disposal of organic waste in landfills.

Applying the waste-to-energy approach in Republic of Serbia and Bosnia and Herzegovina

In the Republic of Serbia, there is no plant for the production of electricity from municipal waste or landfill gas. Eight coal-fired thermal power plants are currently in operation in Serbia. Of the total electricity produced in 2020, these eight thermal power plants produced about 70%, while the remaining 30% comprised renewable energy sources. Of renewable sources, 27% is energy produced in hydropower plants, and the rest are other renewable sources [59].

Currently, 35 biogas plants are operating in Serbia, with an installed capacity of around 34 MW. By 2026, around 55 new plants are expected to be put into operation [60]. In 2022, a modern biogas plant with an installed capacity of 2.4 MW was put into operation in Vrbas. The plant uses sugar beet pulp and organic waste from the sugar industry as raw materials. The resulting biogas is used to produce electricity, and the waste from this plant is turned into fertilizer and liquid filtrate used on agricultural land. This facility operates without generating any waste and serves as an illustration of how the circular economy can be implemented to manage the by-products of sugar production (Fig. 1).

The most significant WtE project in Serbia is the construction of a WtE plant for the utilization of municipal waste in the capital, Belgrade, and the construction of a plant for the utilization of landfill gas at the landfill in the suburban area of Vinča to generate energy. The WtE plant is in the final phase of commissioning and has an installed capacity of 32.24 MW of electricity and 56.5 MW of thermal energy. The plant for the utilization of landfill gas to generate energy has an installed capacity of 3.2 MW of electricity and 2.9 MW of thermal energy. Both plants are supposed to start operating by the end of 2023 [62].

In the municipality of Šamac in Bosnia and Herzegovina, the first biogas plant of the "Buffalo Energy Gold-MG d.o.o. Šamac" company was put into operation (Fig. 2). The installed capacity of the plant is 999 kW of electrical and thermal energy. The efficiency of the biogas plant is manifested in the fact that the waste from one production process (in this case, manure) has become a key raw material in a new production chain: energy production. Through the biogas plant, waste manure is processed into four highly sought-after products: electricity, heat, organic pelleted solid manure, and liquid manure. The gas plant represents a concrete application of the CE principle in waste disposal because a circular approach completely replaced the

Fig. 2 Biogas plant Buffalo Energy Gold-MG d.o.o. Šamac, Bosnia and Herzegovina [63]

Fig. 1 Biogas plant in Vrbas, Republic of Serbia [61]

concept of linearity, and four new products with added value were obtained.

The gas plant receives and harmlessly disposes of other organic waste such as straw, cereals, crop residues, by-products of slaughterhouses, expired foodstuffs, by-products from the production of beer, alcohol, and sugar, whey, and waste from kitchens and restaurants.

The biogas plant for electricity and thermal energy production based on the principle of anaerobic digestion began operating in September 2022 as part of the company "Farma Spreča" d.o.o. in the municipality of Kalesija (Fig. 3). Corn silage, beef manure, and chicken manure are used as raw materials. The electricity produced is delivered to the grid, while the thermal energy is utilized in part to heat the fermenter. The plan is to build greenhouses and glasshouses that would be heated with thermal energy from the biogas plant. The plant has four fermenters, each with a capacity of 150 kWh, and the expected operating time of each is 8000 h per year.

Waste management in the green transition towards a circular economy

The green transition of BIH and Serbia towards CE faces a number of challenges and problems. Some of the key issues for the transition towards CE are [65, 66]:

- Lack of infrastructure: BIH and Serbia have insufficiently developed infrastructure for collecting, sorting, and recycling waste. Most cities have inadequate waste management systems, and the existing ones are not always effective or sustainable. This makes it difficult to achieve CE goals.
- Weak implementation of legal regulations: Although BIH and Serbia have laws and regulations that support CE, the implementation of these legal regulations is often weak or insufficient. There is a lack of strict control over the application of legal regulations, which can lead to inappropriate waste management and insufficient recycling.
- Lack of awareness: Many citizens of BIH and Serbia are not sufficiently familiar with the concept of CE and the importance of sustainable waste management. This makes CE implementation difficult, as insufficient awareness and education can lead to insufficient support for sustainable waste management practice.
- Lack of financial support: The lack of financial support represents another challenge for the transition of BIH and Serbia towards CE. A successful transition towards CE requires a large investment in infrastructure and technology, which these two countries are often unable to finance on their own.

CE represents a model of economic development based on waste reduction, resource reuse, and materials recycling, thereby reducing negative impacts on the environment and production costs.

BIH and Serbia, like most countries in the world, face great challenges in waste management and environmental protection. Therefore, the application of CE could be useful for solving these problems and improving the economic development of a country [67].

Certain activities carried out in BIH and Serbia are directed towards CE. For example, there are initiatives to increase recycling, such as waste collection programs, and there are several businesses that produce recycled products. Moreover, there is interest in the development of the renewable energy industry.

The municipal waste management sectors in BIH and Serbia require the reform in the following segments [68–70]:

- For the creation of legal assumptions for sustainable municipal waste management at the local level, it is necessary to significantly improve the existing system by strengthening the utility companies.
- It is necessary to revise existing plans and make new ones for the construction of regional or inter-

Fig. 3 Biogas plant Farma Spreča d.o.o. Kalesija, Bosnia and Herzegovna [64]

municipal landfills, i.e., for the construction of new municipal landfills or for the improvement of existing ones that, due to geographical location or other obstacles, cannot be merged into a regional/intermunicipal concept. However, such plans should take into account the need to reduce the amount of waste disposed of in landfills and increase the utilization of waste.

- It is necessary to improve the technical capacity of utility companies by acquiring equipment for (separate) collection, removal, and treatment of waste. Actions aimed at reducing waste production and redirecting waste from landfills to other types of processing, including thermal processing and energy utilization, are also needed.
- Developing cross-border cooperation between the Republic of Serbia and Bosnia and Herzegovina is important. Through cross-border cooperation at the state level, it is necessary to work on the coordinated improvement and adoption of new legal regulations in waste management, environmental protection, and the circular economy. Another type of cooperation is possible through the development of laboratories and environmental monitoring in the border area. Existing laws on waste management do not allow cross-border transport of waste from one country to another for disposal. However, cross-border projects can be carried out through the exchange of experience in waste disposal and the application of the principles of the circular economy in waste management, the establishment of common platforms for the exchange of experiences, visits to facilities that represent examples of good practice, the development and implementation of joint educational campaigns, etc.

With the Sofia Declaration on the Green Agenda for the Western Balkans from 2020 [71], the countries of the Western Balkans, including BIH and Serbia as signatories, undertook to implement measures in the field of climate change and pollution prevention, energy development, transport, and CE, as well as the development of biodiversity, sustainable agriculture, and food production. With this declaration, the countries of the Western Balkans should prepare national strategic documents for CE, taking into account the prevention of waste generation, the entire life cycle of products, modern waste management and waste recycling, reuse, repair, and remanufacturing; achieve further progress in the construction and maintenance of waste management infrastructure for cities and regions; design and implement programs to raise awareness among citizens about waste, separate collection and sustainable consumption; and enter into a regional agreement on the prevention of plastic pollution and implement the agreement.

With the previous analysis and results in mind, the research proposes two models necessary for this phase of the transition of the Republic of Serbia and Bosnia and Herzegovina towards the circular economy. They relate to improvements in the domains of governance and management at the local level. The emphasis is on the application of the waste-to-management concept in rural areas occupying a large part of the territory of the mentioned countries, which have poor waste management but generate waste suitable for the application of the waste-to-energy concept.

A novel model for waste-to-energy governance in developing countries

Waste management (WM), particularly solid waste management (SWM) and municipal solid waste management, is a critical component of CE, as it requires reducing waste generation and using waste as a resource. However, effective waste management helps to attain CE by reducing pollution, creating new jobs, and increasing resource reuse [72]. Waste-to-energy conversion is one of the newest forms of waste treatment and offers several advantages. It is possible to produce electricity using incineration or anaerobic digestion and reduce the emission of gases that contribute to global warming. New WtE plants open the possibility of new jobs, create a more efficient waste management system, and contribute to sustainable development goals [73].

Although WtE waste treatment options are mainly established in developed countries such as Italy, Germany, Finland, France, and Japan, there is also potential for their implementation in developing countries such as Serbia and Bosnia and Herzegovina. This fact is supported by data from the Republic of Serbia's strategic and planning documents on sizeable amounts of biodegradable waste that requires appropriate treatment and that is subject to fermentation, anaerobic digestion, and the utilization of landfill gas processes [74, 75]. Given the Republic of Serbia's and Bosnia and Herzegovina's aspirations for EU membership, it can be argued that they bear an obligation to execute the policies and objectives of the EU member states. This obligation has been fulfilled to a significant degree through the enactment of EU legislation within those countries. The EU has recognized WtE as a technology that can contribute to the transition to CE, but only if the waste management hierarchy [76], i.e., the order of priorities in waste management practices, is respected. The facts indicate that the improvement of the waste management system through the implementation of WtE technologies cannot be accomplished in the absence of ongoing national progress, and for sustainable

development to occur, the gradual advancement of the waste management sector must coincide with more extensive social progress [77]. Figure 4 illustrates the hierarchy of WtE technologies applicable to developing and transition economies in accordance with the waste management hierarchy.

Considering the results of the analysis, a proposal is made for the *Model for waste-to-energy management in developing countries*, as illustrated in Fig. 4.

A solid political framework is required for the conversion of waste to energy, logistical planning, provision of financial resources, improvement of infrastructure, public education regarding the importance of waste management, and other aspects of implementing WtE technologies in developing countries. All factors significant for the implementation of WtE technologies in developing countries are combined in the form of *A novel model for waste-to-energy governance in developing countries*, as illustrated in Fig. 5.

The technical aspect of the implementation of WtE technologies must first imply that there is precise data on the amount and composition of the generated waste because this data is fundamental in making informed decisions regarding subsequent waste treatment processes [78]. The waste collection system requires significant improvement, considering the potential for implementing the primary selection of recyclable components of the waste. It is essential to consider the potential for waste reuse and recycling, following the regulations of EU member states and adhering to the waste management hierarchy, as well as the integration of recycling technologies with WtE technologies. In order to effectively implement any waste treatment technology, including WtE technologies, the waste management system as a whole must be substantially enhanced, with infrastructure being the most critical component requiring improvement [79].

The political aspect of implementing WtE technologies requires political will to implement sustainable solutions in the waste and energy sectors. Further harmonization of the existing legal framework with the frameworks of the EU member states is necessary, as is the provision of resources for their implementation. Establishing control mechanisms for the implementation of the provisions prescribed by law is only one of the ways to encourage their strict application. Emission control and monitoring aimed at preventing further environmental degradation should be a top priority for decision-makers. Developing

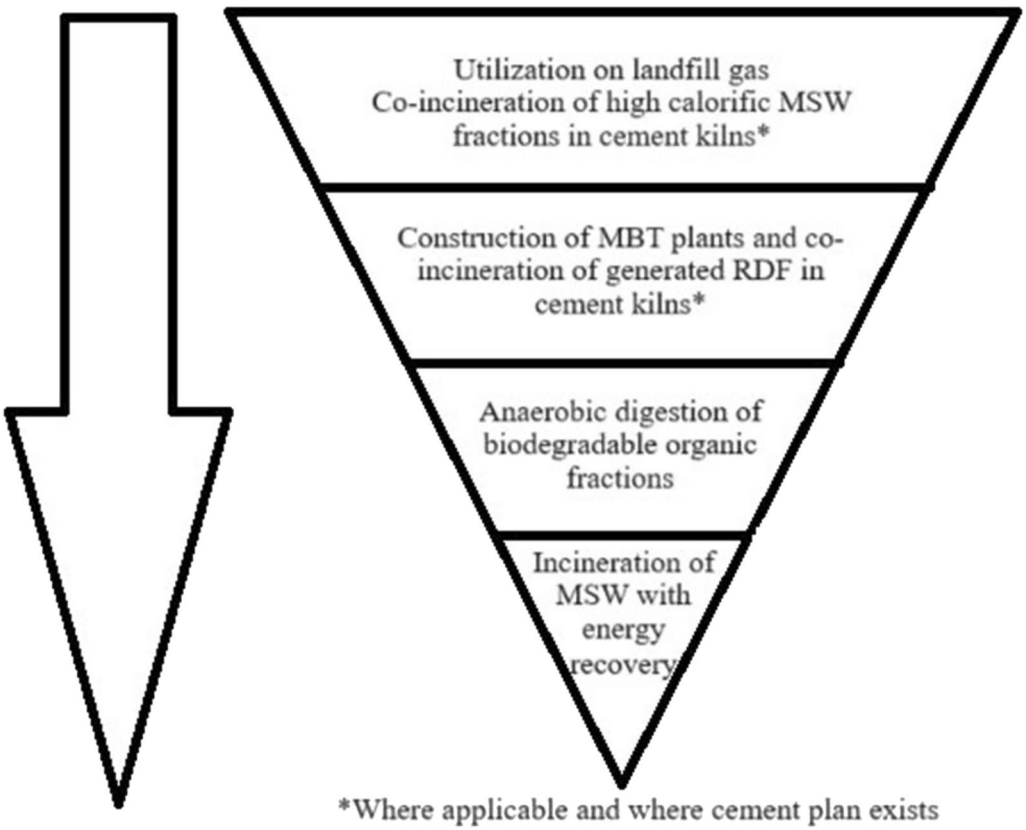

Fig. 4 Proposed initiatives for waste-to-energy management in developing countries (adapted from: Vujić et al. 2017)

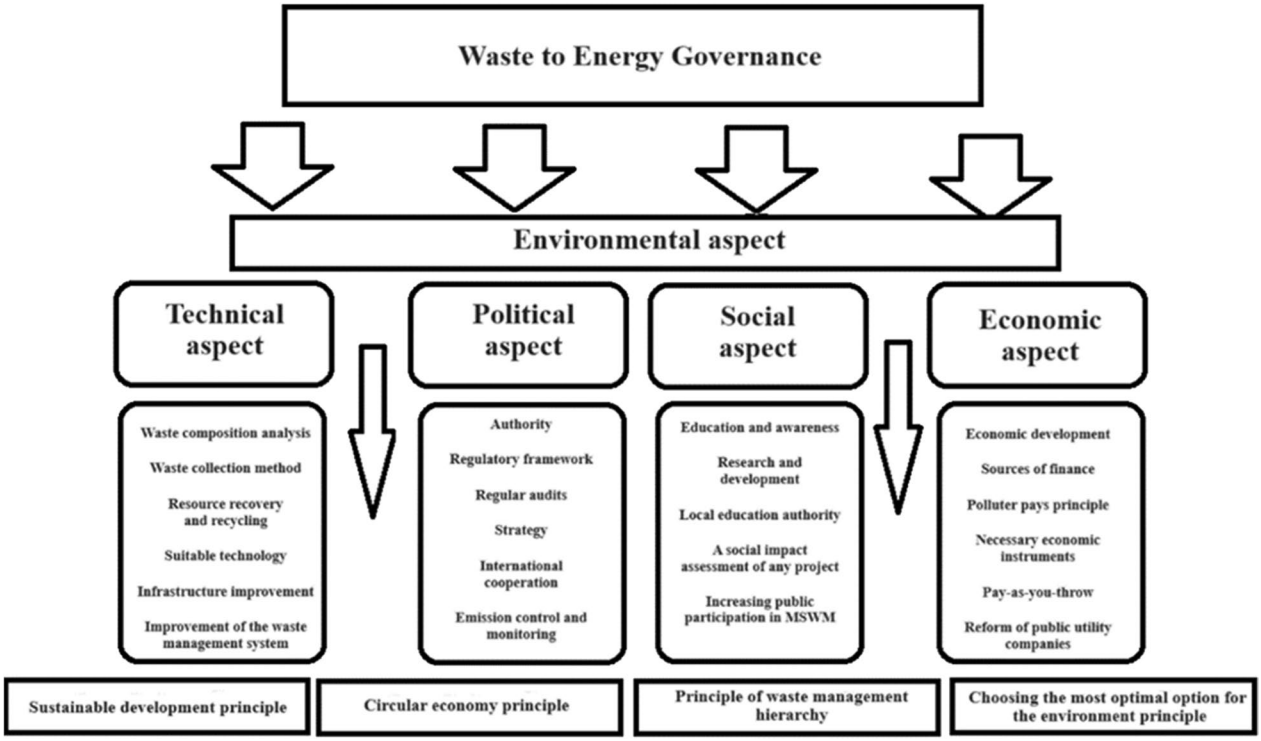

Fig. 5 A novel model for waste-to-energy governance in developing countries

countries should imitate the models of sustainable waste management solutions and foster international cooperation.

An essential aspect in the implementation of WtE technologies is the social aspect. This is evident in the education of employees at all levels of management in the waste sector, in the education of interested households and the general public, and in the efforts to increase public awareness regarding waste as a resource. It is crucial, from a social perspective, to conduct projects that assess the effects of project implementation on the local population and to involve a variety of stakeholders in waste sector decision-making. Research and development is an essential component that should not be disregarded, as it enables the creation of sustainable waste management alternatives.

To implement WtE technologies, the country's overall economic strengthening is necessary to approach the environmental sector as a sector that justifiably demands and requires significant financial resources. Raising the overall standard of the population in developing countries would significantly contribute to improving the entire waste management system. The implementation of the polluter pays principle would allow polluters to bear the total costs of the consequences of their activities, i.e., the costs of waste collection, treatment, and disposal should be included in the price of the product. It is necessary to provide funding sources for WtE projects, which are very demanding financially. It is also necessary to implement other financial mechanisms for the production of energy from waste, including tariffs, fees for waste disposal, subsidies for the production of energy from waste, etc. It is also necessary to reform public companies that deal with solid municipal waste management. All of the mentioned aspects for the implementation of WtE technologies must be viewed through the prism of the impact on the environment, that is, through the implementation of sustainable development goals while respecting the principles of circular economy, the application of the best available solutions for the environment, and the hierarchy of waste management.

A novel model for waste-to-energy management in rural areas of developing countries

The proportion of the Serbian population that received regular waste collection services was approximately 86% in 2019 [80]. In contrast to the lack of regular waste collection services in rural areas, such services are generally more prevalent in urban areas. In mountainous rural areas, collection services are often not available. The proportion of municipalities that provide coverage for these services varies between 25 and 100%, as reported by SEPA [81]. In 2021, 74% of the population of Bosnia and Herzegovina had access to public waste collection

services. While urban areas of the country had coverage between 80 and 90%, in rural areas the percentage was between 40 and 45% [82]. Challenges that rural areas face due to the absence of an organized waste collection and treatment system include:

- Unorganized and ineffective waste collection and disposal leads to the creation of illegal landfills that contaminate agricultural land, underground, and surface water. This can adversely affect human health.
- Burning of agricultural residues without authorization or control is the leading cause of fires in villages.
- Reckless disposal of various types of waste, including waste tires and oils, old electrical appliances, spent batteries and accumulators, medical and construction waste, as well as hazardous packaging from pesticide packaging.

Problems with waste collection in rural areas in both countries are mainly due to the lack of financial resources at the local level for the construction of the necessary infrastructure, the lack of financial resources for the acquisition of waste collection equipment, and the poor organization of the waste management system at the local level.

Limited access to infrastructure and geographical dispersion are frequent obstacles to effective waste management in rural regions. Although there are several obstacles to overcome, sustainable waste management has great potential. The predominant type of municipal waste found in rural regions is bio-waste. Rural households generate substantial quantities of agricultural waste as well.

Four essential methods of processing agricultural waste and the organic part of municipal solid waste suitable for rural areas are the use of waste as animal feed, briquette production, biogas production, and composting, along with other solid waste recycling approaches [83].

Figure 6 illustrates a novel scheme for potential waste management in rural areas without organized waste collection.

The presented model suggests using small home biogas plants (biodigesters) that are easy to assemble and use for energy production from waste. Small-scale

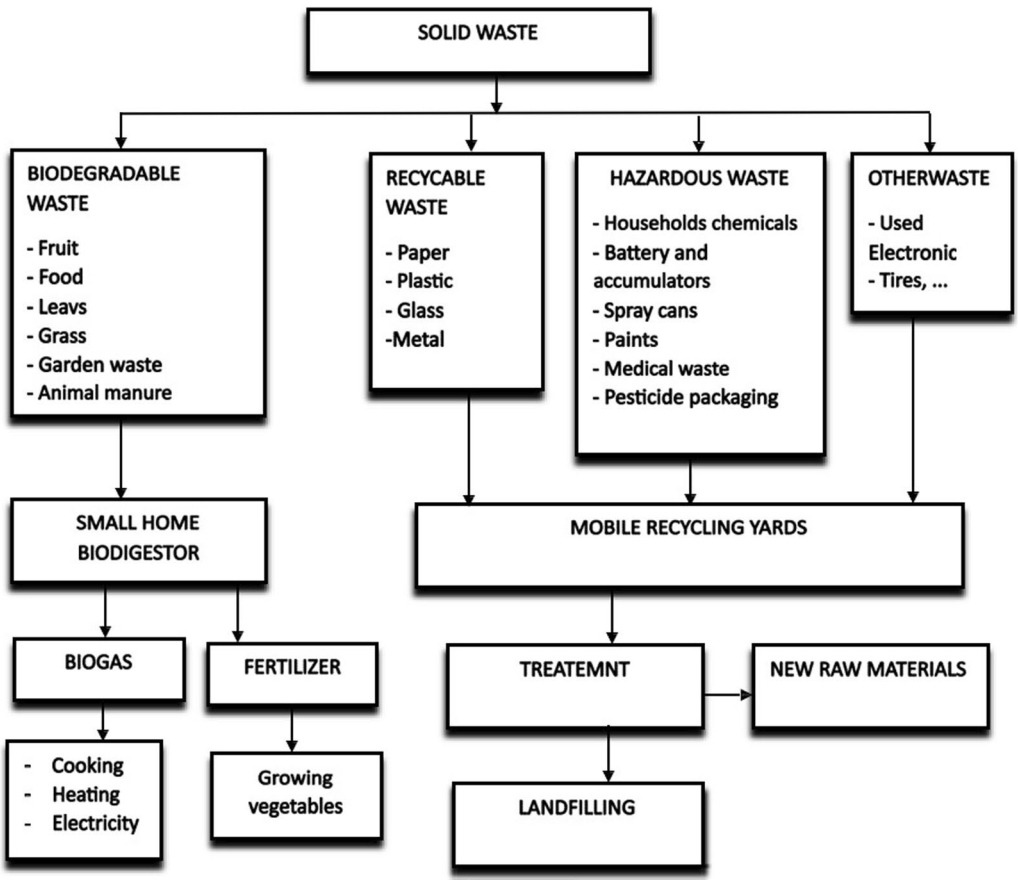

Fig. 6 A novel model for waste management in rural areas

biogas plants installed in households would use organic waste, such as food scraps and agricultural waste (crop residues and manure), to produce biogas that could be used as an energy source for cooking, heating, and lighting. Digestate is obtained as a by-product of this process, which can be used as a natural fertilizer for agriculture (Fig. 7).

To produce biogas for two hours of cooking on one high fire, six liters of organic waste (food waste, including fruit and vegetables, grains, peels, cooking oil, dairy products, and meat) should be added per day to a home biodigester. Animal manure can also be used. For the same cooking time, 20 L of animal manure are needed. When small household digesters are used to treat organic waste, GHG emissions into the atmosphere are reduced (about 6 tons of CO_2 emissions per plant per year).

Biogas is safe to work with because it is uncompressed and less dangerous than LPG or propane, which are stored under high pressure. In addition to biogas, biodigestate is also obtained as a product that can be used as a biofertilizer (it contains nitrogen, potassium, calcium, magnesium, phosphorus, sulfur, and iron). This biofertilizer is in a liquid state, easily absorbed, and saves time and labor when composting waste and using compost as fertilizer. Also, in this way, the problem of unpleasant odors that occur when processing organic waste would be solved [84].

According to the model illustrated in Fig. 6, inorganic waste from households in rural areas without organized waste collection would be separated into recyclable waste (paper, cardboard, plastic, glass, and metal), other waste, and hazardous waste. All these wastes would be delivered to mobile recycling yards that would be emptied once a month or as needed (Fig. 8).

In this way, residents of rural areas would be able to hand in their recyclable waste and receive a certain allowance for it. Other waste, including hazardous waste, would be disposed of in appropriate containers within the recycling yard. These yards would also provide a safe place to collect and transport all types of waste to appropriate facilities or centers for processing. Collected waste from mobile recycling yards would be submitted for further treatment and final disposal.

Cooperation between local authorities, organizations, and communities is necessary to implement such a system successfully. Through this integrated approach, rural areas would not only achieve efficient waste management, but also contribute to preserving the environment and improving the quality of life of their residents.

Conclusion

The transition to a circular economy (CE) and effective solid waste management are key to sustainable development. The current linear economic model based on the take–make–dispose approach faces physical limits, as global waste production is predicted to reach billions of tons per year by 2030. The circular economy, on the other hand, emphasizes the reduction, reuse, recycling, and recovery of materials in order to extend their service life and reduce waste.

The European Union has established legal frameworks, such as the Waste Framework Directive and the Circular Economy Strategy, to promote waste reduction, recycling, and waste use as a resource. Implementing a

Fig. 7 Small biogas digester (Source: https://cleantechnica.com/files/2017/11/homebiogas-details.jpg)

Fig. 8 Mobile recycling yard (Source: https://kova.hr/products/mobile-recycling-yard-1038/)

circular economy presents challenges, especially in developing countries such as Bosnia and Herzegovina and Serbia, where limited resources, infrastructure, and financial capacity can hinder progress. However, with the right approach and support, the circular economy can contribute to reducing poverty, increasing productivity, and protecting the environment.

This paper is focused on an overview of the state of solid waste management in Bosnia and Herzegovina and Serbia. The amount and composition of waste in these countries depend on economic conditions, living standards, urbanization, and population size. The composition of municipal solid waste varies, but biodegradable waste is often the dominant fraction, followed by recyclable materials such as plastic, metal, glass, paper, and cardboard.

In order to progress towards a circular economy in Bosnia and Herzegovina and Serbia, it is essential to address challenges related to legislation, infrastructure development, financial resources, and public awareness. Improving waste management practices, promoting resource efficiency, and implementing innovative solutions can contribute to the transition to a circular economy, which leads to environmental protection, economic growth, and poverty reduction.

The authors propose that, in light of the research findings and the unique circumstances of the Republic of Serbia and Bosnia and Herzegovina, the implementation of reforms in the areas of governance, waste management, and legislation should be a top priority. This is particularly crucial in rural areas, which face the greatest waste-related challenges but have the greatest potential for implementing the waste-to-management concept. Two novel models for development in this domain—waste governance and waste management in rural areas—are introduced in this paper as prerequisites for establishing an effective pathway to a circular economy.

Taking everything into consideration, embracing circular economy principles in solid waste management can help these countries achieve sustainable development goals, reduce waste generation, and maximize resource value. By adopting a holistic and systemic approach, participants can collaborate across sectors and overcome administrative barriers, thus ensuring efficient use of resources and minimal waste generation. As a transformative approach toward a more sustainable and prosperous future, the circular economy offers opportunities for innovation, job creation, and environmental protection.

Studying the best practices of other countries that have successfully implemented the circular economy concept should be a key component of future research. These studies should provide insight into different strategies, policies, and approaches that have proven successful in other countries. The identification of applicable models for Bosnia and Herzegovina and Serbia based on these best practices can be essential

for drafting guidelines and recommendations for the implementation of the circular economy while taking into account local specificities and resources.

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DB, DNM and BM prepared a draft of the study and overview for Bosnia and Herzegovina. AAP and DP prepared and overview for Republic of Serbia. All authors read and approved the final manuscript.

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