

CURRENT STATUS AND IMPACT OF RECYCLING IN REPUBLIC OF SERBIA

SITUAÇÃO ATUAL E IMPACTO DA RECICLAGEM NA REPÚBLICA DA SÉRVIA

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Abstract

One of the biggest challenges of modern society is the management of spent and discarded materials. Due to the continuous growth of the world's population, waste generation is steadily increasing. The aim of this paper is to present the current state of the art of recycling in the Republic of Serbia, emphasizing the importance of understanding the basic elements of waste management. The implemented laws and regulations in the field of waste management provide a solid foundation for further progress in this area of environmental protection. The primary stages of proper waste management include: (1) generation, (2) collection, (3) sorting, (4) transportation and distribution, and (5) treatment or disposal. Selecting an effective solid waste treatment process remains challenging due to the variability and composition of input materials. In 2024, a total of 8.15 million tonnes (Mt) of waste was generated in the Republic of Serbia, of which 0.11 Mt was classified as hazardous. Therefore, appropriate waste management represents one of the most important components of a functional green economy, promoting environmental protection and the social sustainability of local communities.

Keywords: Circular Economy. Environmental Protection. Sustainable Development. Waste Treatment.

Resumo

Um dos maiores desafios da sociedade moderna é a gestão de materiais usados e descartados. Devido ao crescimento contínuo da população mundial, a geração de resíduos aumenta constantemente. O objetivo deste artigo é apresentar o estado atual da reciclagem na República da Sérvia, enfatizando a importância de compreender os elementos básicos da gestão de resíduos. As leis e regulamentações implementadas na área de gestão de resíduos fornecem uma base sólida para o progresso futuro nesta área de proteção ambiental. As principais etapas de uma gestão adequada de resíduos incluem: (1) geração, (2) coleta, (3) triagem, (4) transporte e distribuição e (5) tratamento ou disposição final. A seleção de um processo eficaz de tratamento de resíduos sólidos continua sendo um desafio devido à variabilidade e composição dos materiais de entrada. Em 2024, um total de 8,15 milhões de toneladas (Mt) de resíduos foi gerado na República da Sérvia, dos quais 0,11 Mt foram classificados como perigosos. Portanto, a gestão adequada de resíduos representa um dos componentes mais importantes de uma economia verde funcional, promovendo a proteção ambiental e a sustentabilidade social das comunidades locais.

Palavras-chave: Economia Circular. Proteção Ambiental. Desenvolvimento Sustentável. Tratamento de Resíduos.



1 INTRODUCTION

The foremost factors of the waste's amount rise were marked as global industrialisation and an increasing number of people around the world (Demirbas, 2011). The potential for significant increases in waste generation in places which are currently defined by modest incomes and poor socioeconomic scores is indicated by the strong associations among economic growth and waste creation (Mayer *et al.*, 2019). Simultaneously, climate transformation and global warming are detected as tightly linked issues of modern society. As a result, immediate action must be taken to lessen detrimental effects of accumulated waste on the environment and public health. Therefore, in order to advance sustainable development on a global scale, it is imperative that natural resources are utilized in a prudent manner.

Appropriate treatment of waste techniques are becoming more crucial in the context of circular economy. The process of retrieving resources or worth from waste is referred to as recycling, involving recovering or reusing the disposed materials. There are several ways to recycle waste, including extracting and reprocessing the basic materials or converting the waste's heat content into electricity (Pilapitiya *et al.*, 2024). Innovative recycling methods, such as energy recovery (Yi *et al.*, 2018; Ohnishi *et al.*, 2018; Dlamini *et al.*, 2019), biological (Koshti *et al.*, 2018; Pollmann *et al.*, 2018; Zaborowska & Bernat, 2023), chemical (Eneh, 2021; Lee & Liew 2021; Risco & González-Egido, 2021) and physical (Ventura *et al.*, 2018; Li *et al.*, 2024) processing, are constantly being developed. Awareness and education about waste and waste economy is growing increasingly important from a global perspective on resource conservation.

By lowering the quantity of waste placed in landfills, high recycling rates assist local governments in lowering waste disposal expenses and mitigating adverse environmental effects (Bayar *et al.*, 2021). Inadequate waste management can lead to the several accidents, such as explosions, fires, and following contamination of the surrounding air, soil, and water (Gutberlet & Uddin, 2017; Siddiqua *et al.*, 2022). In the same manner, incorrect management and disposal can result in costly remediation efforts and put nearby communities in risk. Along with these issues, improper disposal of waste raises greenhouse gases emissions, especially contribute to climate change and global warming. Therefore, inducing a long-term integrated solid waste management can reduce

the detrimental effects (Demirbas, 2011; Longfor *et al.*, 2023). Assessing local requirements and circumstances is necessary for selecting the best solid waste management techniques. The category of waste and the appropriate management plan for it will determine the collecting techniques, the possibility of reuse or recycling, and the sort of treatment that could be given to these resources.

Republic of Serbia, as candidate for European Union membership, was adopted several regulatives and implementing them with an aim to improve quality of the environment. The Directive on waste requires EU member states to recycle at least 60% of municipal waste by 2030 and 65% until 2035 (Directive 2025/1892, 2025; Directive 2008/98/EC, 2025). This Directive has been transposed into the Serbian legal system through the Law on Waste Management ("Official Gazette of the RS", No. 109/2025, 2025) and the Waste Management Program of the Republic of Serbia 2022–2031 (Government RS, 2022). The aim of this Program is to increase the municipal waste recycling rate to 35% by 2030. On the other side, there is Regulation on the Adoption of the Packaging Waste Reduction Plan for the period 2025–2029, with more ambition aim to achieve the recycling of 65% of packaging waste and municipal packaging waste by 2029.

Circular economy (CE) measures directly contribute to higher recycling rates. Because of that, Regulatory frameworks of circularity are highly important. In EU, main documents are European Green Deal and Circular Economy Action Plan (CEAP). For Serbia, most important are Green Agenda for the Western Balkans (GAWB) Action Plan 2021-2030 and Revised Action Plan for the Implementation of the Sofia Declaration on the Green Agenda for the Western Balkans 2025-2030, where packaging waste recycled target is $\geq 50\%$ by 2030 (The Regional Cooperation Council, 2025).

The main goals of this paper were to show the most recent data (2023, 2024) from Waste Reports from Serbian Agency for Environmental Protection (SEPA). Therefore, classification of generated waste was presented together with some other indicators such as hazardous/non-hazardous, type of waste, *etc.* Besides, legislative reflected in enacted laws and rulebooks in area of waste management and treatment in Republic of Serbia are presented. Synergical effects of technological solutions, application of legal regulations and environmental awareness could pose positive solution for dealing pollution around

globe. Implementation of the circular economy (CE) principles and waste hierarchy (R's pyramid) are auxiliary tools for reaching set goals.

2 METHODOLOGY

The methodology is grounded in both an organized approach and universal principles of scientific understanding. This study is founded on pertinent and accessible academic research and review articles published in the last 18 years, comprehending different research areas into one synergistic approach. The study describes the patterns of:

- (1) Information of applied best available techniques for waste management, proper waste hierarchy and waste classification;
- (2) Data of quantity and quality of waste generated in the territory of Republic of Serbia with prediction of future trends;
- (3) Legislative of waste management and state of art in Republic of Serbia.

3 WASTE MANAGEMENT, HIERARCHY, AND CLASSIFICATION

The linear economic model has experienced unmatched expansion as the globe moves toward an urban future. Also, it has put significant strain on the environment due to natural resource threats and waste creation (Zhang *et al.*, 2022). The waste hierarchy is closely linked to the circular economy's R-based concept. By implementing the reduce-reuse-recycle (3Rs) concept an alternative CE would effectively close loops in industrial systems (Ghisellini *et al.*, 2016). Either the CE or the waste hierarchy take into account a product's entire life cycle, comprising its pre-use, usage, and post-use phases (Das *et al.*, 2025). They both have been developed over time to highlight how a product is designed and used before it becomes waste. As a result, it is clear that the CE and waste hierarchy have a same concept of managing waste through rethinking, redesigning, and repurposing in order to increase a product's environmental sustainability and decrease waste generation and negative effects (Ghisellini *et al.*, 2016; Kirchherr *et al.*, 2023).

As a result, waste management has emerged as a crucial component of sustainable development and environmental preservation, and it must be handled using appropriate management practices, scientific methodologies, and awareness.

Despite there are no indicators for the adoption of it, the waste hierarchy has been considered in both national and international rules. Waste hierarchy was added to the 2030 Agenda for Sustainable Development's Sustainable Development Goal (SDG) (United Nations, 2015). The metric most frequently used is the recycle percentage, which can show progress the hierarchy and is easy to measure (Haupt *et al.*, 2017). It is possible to design waste management processes with high recycling rates and high disposal or incinerator levels at the same time (Iacovidou *et al.*, 2026). This complex system often makes the position difficult for all interested parties.

According to Waste Framework Directive EU (Directive 2008/98/EC, 2008) a five-step waste hierarchy is used by the directive to prioritize waste treatment: avoidance, preparation for reuse, recycling, additional recovery, and disposal.

The fundamental component and prerequisite for effective waste management is a appropriate waste categorizing framework. Among all parties involved, especially officials, waste producers, and recyclers, waste classification systems are essential. Waste categories are intended to make data collecting, tracking, and supervisory easier for environmental management authorities, as well as to help them create appropriate waste management policies (Wen *et al.*, 2014). Waste classification systems can assist generators cut expenses by preventing the need for final waste treatment solutions. Recyclers will prioritize waste classification in order to minimize threats to the environment, safeguard the health of their employees, and maximize profits. Making this distinction is crucial to following environmental regulations and reducing the carbon footprint caused by human activity (Kan, 2009).

Depending on management techniques, waste categories can include multiple layers. Waste can be classified according to its source, composition, safety, biodegradability, and physical state (solid, liquid, or gaseous), among other criteria (Ayilara *et al.*, 2020). Waste might be classified as either municipal solid waste or industrial waste depending on the source of generation (Ghazali *et al.*, 2022). Waste can be separated into hazardous and non-hazardous categories based on harmful qualities.

Worldwide waste creation is expected to exceed 3.40 billion tons by 2050, according to a 2018 World Bank research (Kaza *et al.*, 2018), while the 50% is organic-based. Today, each person generates about 0.74 kilogram of waste every day (Sarker *et al.*, 2024).

4 OVERVIEW OF PRIMARY TREATMENTS OF WASTE-TO-ENERGY

To improve clarity, the review provides a brief overview of the technology under evaluation. There are already above 1700 treatment factories worldwide. At 62%, Asia Pacific has the highest percentage, subsequent to North America at 4.5% and Europe at 33% (Malav *et al.*, 2020). While solid waste-based technologies have advanced, they still face challenges such as inconsistent waste compositions, intricate treatment plant setups, and possible air pollution (Varjani *et al.*, 2022). Various thermochemical and biochemical processes can be used to convert waste into energy-rich products. Extended processing times, significant capital costs, and extremely low operating costs are typically required. Conversely, thermochemical conversion technologies are effective and suitable ways to produce energy and value waste (Shahnazari *et al.*, 2020; Petrović *et al.*, 2021). Prominent thermochemical waste-to-energy methods include anaerobic digestion, incineration, pyrolysis, gasification, and combustion (Sarker *et al.*, 2024).

Environmental cost and economic cost are often the criteria that influence the choice of treatment facility. The environmental impact of greenhouse gas (GHG) emissions and the ensuing climate change from various treatment techniques are taken into consideration while evaluating environmental cost (Yilmaz, 2025).

4.1 Pyrothermal treatment

Pyrolysis is a heating procedure that disintegrates waste at temperatures between 300 and 1000°C without addition of gaseous oxygen. This method creates syngas, biooil, and char (Varjani *et al.*, 2022). Product quality and yield are affected by pyrolysis factors, including temperature, heating duration, retention time, waste input mix, and the size of the particle (Beyene *et al.*, 2018). Greater reaction temperatures typically encourage volatile cracking, dehydration, decarboxylation, and secondary decomposition of biochar,

increasing syngas generation at the expense of yields of biochar and biooil (Chintala, 2018). Furthermore, a prolonged retention period accelerates recondensation, repolymerization, and secondary breakdown processes, increasing the output of biochar.

4.2 Hydrothermal treatment

The desired result of hydrothermal processing is biocrude oil, with solid, gaseous, and liquid phases as byproducts. This process is carried out in a solvent medium temperatures (250–375°C) and high pressures (5–25 MPa). By removing the expensive drying step and reducing the energy needed, this innovative method is appealing for the direct transformation of wet biomass into liquid fuel. Liquefaction produces value-added products like glue, epoxy, resins, biopolymers, and polyurethane foams in addition to biocrude oil (Li *et al.*, 2017; Jiang *et al.*, 2018).

4.3 Gasification

Gasification is additional thermal waste to energy transformation method for waste management (Fang *et al.*, 2021). Organic materials undergo partial oxidation at temperatures between 500–2000 °C in an oxygen and air environment that is sufficiently regulated (Zhang *et al.*, 2019). Syngas is the main byproduct of this technique. The chemical sector is one among those subsequent applications, where it can be converted into ethanol or used as fuel to generate thermal energy or electricity (Foster *et al.*, 2021).

4.4 Anaerobic digestion

Similar to gasification, anaerobic digestion is a proven method for treating organic waste in various industries. Anaerobic digestion typically involves four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Koyama *et al.*, 2017). Depending on the kind of raw material, hydrolysis is the rate-limiting stage in the anaerobic digestion process. To improve the product gas yield and shorten the digestion time, the biomass needs to be prepared. Methane (around 60%) and CO₂ constitute the majority of the resultant biogas (Varjani *et al.*, 2022).

4.5 Controlled landfilling

Unfortunately, methods of landfilling is frequently employed process of waste discharging. Some data show that in India more than 90% is disposed of in unsanitary landfills, while the less than 15% of the generated waste should be disposed of. In that way, limited areas are left for agricultural production and urban spaces (Hatab *et al.*, 2019; Huo, 2024). Second negative aspect of landfilling is formation of gaseous with global warming potential such as methane (Lou & Nair, 2009). If it is not controlled, it could cause several negative contributions. Some modern plants are collecting methane, and use it for energy consumption.

4.6 Combustion

One common method of treating materials is incineration, which can reduce waste bulk volume by 70–90% and is suitable for wastes with greater calorific values. It can be described as an almost fully oxidative process of initial waste stream (Foster *et al.*, 2021). This procedure creates electricity from the generated energy (Kalyani *et al.*, 2014). Typically, incineration involves burning waste at temperatures between 800 and 1200 degrees Celsius while excess oxygen or air is present (Nanda & Berruti, 2021). MSW is ignited through a series of phases that include heating and drying, devolatilization and decomposition, and the combustion of char and volatiles (Nunes *et al.*, 2014). The principal strength of this method compared to the abovementioned is the possibility of using all types and classes of waste, as a base input for generation of energy and heat power.

In Serbia, incineration treatment plant Vinča, near capital city Belgrade, is the newest treatment facility. Plant that generates 56 MW of thermal energy started to work in 2023, treating up to 340,000 tons of waste annually (Beo Čista Energija, 2024)). This plant helps in reducing deposited waste on sanitary landfills and also helps in closing unsanitary landfill used for more than four decades.

5 SERBIA: CURENT STATE OF ART

Republic of Serbia has population of around 6.69 million of residents' (Statistical Office of the RS, 2022) with territory positioned on Balkan peninsula in South-East Europe. As a "state candidate" for becoming member of European Union, country constantly improving its legislation in the field of waste treatment and environmental protection, in accordance with negotiating chapter 27.

The Serbian Environmental Protection Agency (SEPA) receives data of generated waste from local municipalities through public utility corporations (PUC). During the 2024, 99 PUCs produced reports, compared to 95 PUCs in 2023 (SEPA, 2023; SEPA, 2024).

Due to the launch of municipal waste incineration at the landfill "Vinča" and a decline in the Republic of Serbia's citizenry, there is a tiny reduction in the quantity of produce municipal waste, but the amount of gathered and discarded waste is roughly the same as in 2023 (Table 1).

Table 1

Indicators related to municipal waste (SEPA, 2023; SEPA, 2024)

Indicator	2024*	2023**
Total amount of municipal waste generated (million t)	2.89	3.07
Recycled fractions of municipal waste (million t)	0.418	0.484
Exported municipal waste fractions (million t)	0.115	0.115
Amount of collected and deposited waste (million t)	2.38	2.59
Average waste collection coverage (%)	88.1	88.3
Average daily amount of municipal waste per capita (kg)	1.20	1.26
Municipal waste recycling rate %	17.6	15.5

* Estimated based on population number in 2023

** Estimated based on population number in 2022

This is demonstrated by the fact that the median daily waste production has somewhat decreased while the total amount of municipal waste generated has also decreased. The extent of municipal waste collection is comparable to what it was in the

past. The municipal waste recycling level is 17.6%, which is slightly fewer than the previous year (SEPA, 2024). Total amount of landfilled municipal waste was 1.109.461 t, while the incinerated amount was 288.829 t. So far, 12 sanitary landfills have been built in the Republic of Serbia, of which ten are regional and two are local, together with one thermal waste processing plant “Vinča“.

The SEPA also receives reports from companies about the waste they generate during operations and how they manage that waste. According to the reports obtained, in the Republic of Serbia was created 7.84 Mt of waste in 2023, of which 90,000 t was hazardous waste (SEPA, 2023). The biggest manufacturers of waste are thermal power plants. 5.87 Mt, or 75% of the entire quantity of waste created, was made up of coal fly ash slag and dust.

During the 2024, in the Republic of Serbia was produced 8.25 Mt of waste, of which 104 kt was hazardous. Again, the thermal power plants were the largest producers of waste. Coal fly ash and ash, slag and dust, which are marked 10 01 in the Waste Catalogue, were generated in an amount of 6.01 Mt, or 73% of the total amount of waste produced (SEPA, 2024).

According to statistics collected and filed *via* the Agency's database, Table 2 displays the amounts of waste produced throughout business operations by origin for 2023 and 2024. Generated waste in mine industry was excluded from gathering information on the amounts and type due to Law of Mining and *Geological Explorations* ("RS Official Gazette", no. 101/2015, 2015).

Table 2

Recorded quantities of waste produced by origin, excluding municipal waste from households (SEPA, 2023; SEPA, 2024)

Group	Activity during which waste is generated	2024		2023	
		Quantity of non-hazardous waste (t)	Quantity of hazardous waste (t)	Quantity of non-hazardous waste (t)	Quantity of hazardous waste (t)
1	Mining	/	/	/	/
2	Agriculture and food processing	283,489	1	232,302	2
3	Wood industry, paper, cardboard	58,021	0	55,219	1
4	Leather, fur and textile industry	13,059	1	13,062	
5	Oil, natural gas and coal processing	233	4771	0,001	4,383
6	Inorganic chemical industry	5,156	2,144	152	224
7	Organic chemical industry	16,422	392	11,590	453
8	Coatings, adhesives, sealants and printing inks	1,213	1,082	964	1,096
9	Photography industry	73	25	55	44
10	Waste from thermal processes	6,527,263	26,118	6,447,587	16,940
11	Protection of metals and other materials	1,388	3,191	1,180	1,401
12	Shaping and surface treatment of metals and plastics	69,549	1,905	56,051	522
13	Waste oils and liquid fuel residues	0	7,389		6,960
14	Waste organic solvents, refrigerants	0	22		24
15	Packaging waste, absorbents, wiping cloths	163,973	3,355	177,332	3,337
16	Waste not otherwise specified in the catalogue	41,627	13,598	61,894	13,108
17	Construction and demolition waste	412,124	14,457	302,615	10,830
18	Health protection of people and animals	239	4,475	354	3,811
19	Waste from waste treatment plants	469,348	17,677	275,591	19,044
20	Municipal and similar waste	88,316	3,916	118,341	7,966
	Sum	8,151,493	104,520	7,754,291	90,147

Different classes of waste (19 classes) were produced in several industrial areas. It is evident from the amount of waste formed that there was a 14% rise in hazardous waste and a more than 0.39 Mt rise in non-hazardous waste.

The amount of waste that dropped in the waste producer's warehouse is shown by the difference between the amount generated and the amount submitted for additional treatment (Table 3).

Table 3

Method of dealing with the waste produced (SEPA, 2023; SEPA, 2024)

Year	Indicator	Produced (t)	Delivered for temporary storage to another company (t)	Submitted for disposal (t)	Submitted for reuse (t)	Export (t)
2024	Hazardous	104,519	24,492	9,596	45,018	22,541
	Non-hazardous	8,151,493	336,842	569,673	1,298,630	19,532
2023	Hazardous	90,147	31,954	9,043	47,976	10,852
	Non-hazardous	7,754,291	386,468	437,395	1,251,001	207,290

When it comes to hazardous waste, it is evident that more was submitted for disposal than was created. This is because, in 2023, several businesses submitted waste from prior years for additional treatment. Significant amounts of hazardous waste are still present in producer warehouses, even though more hazardous waste was submitted for treatment than was produced during the year. In the reporting year, the facility that produced coal fly ash stored 5.47 Mt of non-hazardous waste in its warehouse. This amount is the largest representation of coal fly ash.

6 CIRCULARITY IN SERBIA

Every country has a different and distinct transition process to CE. A multi-year systemic methodological approach to sustainable development, resource conservation, and environmental pollution reduction that improves people's health is the shift to a CE. It encompasses all facets of society and all domains that, in the framework of the CE, must be founded on unambiguous business principles.

The CE has been recognized as an important strategic concept for the green transition of the Republic of Serbia, which has been placed high on the list of priorities for the development of our society in recent years. Green transition is a process that

involves economic, energy and investment transition, which are based on the sustainable use of resources and energy, reducing the negative impact on the environment, the application of innovations and digital tools, knowledge, added value and greater competitiveness of the economy (Söderholm, 2020).

Currently, the Republic of Serbia is in the process of adopting the Program for the Development of Circular Economy for the period 2026–2030 (SEPA, in preparation). This strategic proposal aims to institutionalize a transformative framework by aligning industrial productivity with environmental sustainability. Its core objectives include the systemic integration of waste-to-resource pathways, the promotion of green public procurement, and the technical empowerment of small and medium-sized enterprises (SMEs) to adopt closed-loop production models. By prioritizing these specific pillars, the Program seeks to bridge the existing implementation gap and accelerate Serbia's integration into the European circular market.

The Ministry of Environmental Protection is the implementing partner of the project "Reducing the carbon footprint of local communities by applying the principles of the CE in the Republic of Serbia" which will last until 2027 (UNDP RS, 2022). The project supports innovation, which improves cooperation between scientific and research organizations and the economy. As part of the Circular Communities project, and as an activity of the CE Development Program in the Republic of Serbia, in 2023, the development of guidelines for the management of construction and demolition waste began.

The Ministry of Economy, in cooperation with the Circular Economy Center of the Serbian Chamber of Commerce, held a series of activities aimed at promoting the green economy and educating business entities in the application of CE solutions during 2023. The Ministry of Science, Technological Development and Innovation is implementing several Eureka projects related to the CE within the framework of international cooperation.

7 THE LEGAL FRAMEWORK OF WASTE MANAGEMENT

The legislative framework of waste management in the Republic of Serbia cannot be examined in isolation from the legal framework of the European Union. This is due to the gradual harmonization of national waste management legislation with the EU *acquis communautaire*.

7.1 The legal framework of waste management in the european union

The European Union waste management legal framework is composed of several types of legal instruments, primarily directives and regulations, complemented by decisions, action plans, and strategic policy documents. Directives constitute the core legislative mechanism, setting binding objectives—such as recycling targets and waste hierarchy obligations—while leaving Member States discretion as to the form and methods of implementation through national legislation. In contrast, regulations are directly applicable in all Member States without the need for transposition, ensuring a uniform and immediate legal effect.

The most significant EU directives governing waste management and recycling are presented in the table below (Table 4).

Table 4

Directives of waste management in the EU

Directive	Scope	Relevance for Recycling
Waste Framework Directive (Directive 2008/98/EC, as amended by Directive 2018/851, 2018)	Establishes the waste hierarchy, recycling targets, extended producer responsibility (EPR), and separate collection obligations.	The Directive on waste requires EU member states to recycle at least 60% of municipal waste by 2030 and 65% until 2035.
Packaging and Packaging Waste Directive (Directive 94/62/EC, 1994, as amended by Directive 2018/852, 2018)	Regulates packaging waste prevention, reuse, recycling targets, and producer responsibility schemes.	In order to support the achievement of targets to increase recycling and reduce disposal of waste set out in Directive 2008/98/EC and Council Directive 1999/31/EC (14), all shipments of waste destined for disposal in another Member State should be prohibited as a general rule.
Single-Use Plastics Directive (Directive (EU) 2019/904, 2019)	Targets reduction, separate collection, and recycled content in plastic products.	From 2030, beverage bottles listed in Part F of the Annex contain at least 30 % recycled plastic, calculated as an average for all such beverage bottles placed on the market on the territory of that Member State.

The continued reliance on directives reflects the EU’s preference for regulatory convergence through minimum harmonization, allowing Member States to adapt waste management systems to national institutional and infrastructural specificities.

In the following table (Table 5) are outlined the most relevant regulatory instruments shaping the legal framework of waste management and recycling in the EU.

Table 5

Regulations of waste management in the EU

Regulation	Scope	Relevance for Recycling
Packaging and Packaging Waste Regulation (PPWR) (Regulation (EU) 2025/40, 2025)	Harmonizes rules on packaging design, recyclability, labeling, reuse quotas, and waste prevention.	Target to recycle by 31.12.2030, a minimum of 70 % by weight of all packaging waste generated
Batteries Regulation (Regulation (EU) 2023/1542, 2023)	Covers the full lifecycle of batteries, including EV batteries—collection, recycling efficiency, material recovery, and recycled content.	No later than 31.12.2031, all recycling shall achieve at least the following targets for recovery of materials: (a) 95 % for cobalt; (b) 95 % for copper; (c) 95 % for lead; (d) 80 % for lithium; (e) 95 % for nickel.
Regulation on shipments of waste (Regulation (EU) 2024/1157, 2024)	Regulates the transboundary shipment of waste within the EU and	Plays a crucial structural role by: preventing illegal or sham

	between the EU and third countries, including procedures for notification, control, export restrictions, and measures to prevent illegal waste trafficking, ensuring environmentally sound management of waste intended for recovery or disposal.	recycling, ensuring environmentally sound recovery operations, strengthening enforcement mechanisms, and supporting the internal market for secondary raw materials
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The growing use of regulations in the field of CE indicates a shift toward stronger legal harmonization and centralized governance, particularly in areas requiring uniform technical standards and market integration across the EU.

7.2 The legal framework of waste management in the republic of serbia

In the Republic of Serbia, the legal framework of waste management is established through a combination of primary legislation, secondary legislation, and strategic planning documents aimed at aligning national practices with the EU *acquis communautaire*. This regulatory system defines institutional competences, waste streams management obligations, recycling targets, extended producer responsibility mechanisms, and reporting requirements. Through progressive legislative harmonization and the adoption of sector-specific by-laws, Serbia seeks to strengthen recycling performance and transition toward a CE model, particularly in the municipal and packaging waste sectors.

The most important legal instrument in the Serbian waste management framework is the Law on Waste Management (Official Gazette of RS No. 109/2025, 2025). Through this law, the Waste Framework Directive has been transposed into the Serbian legal system. The adoption of a completely new Law on Waste Management in December 2025 marked a decisive step toward alignment with EU standards. The Law constitutes the overarching and systemic legal framework governing waste management in the Republic of Serbia. As a general legal act, it applies to all entities involved in waste generation, collection, transport, treatment, and disposal, unless otherwise regulated by specific sectoral legislation. This law no longer conceptualizes waste as simple refuse, but rather as a resource that must remain within the economic cycle for as long as possible. It

incorporates the fundamental principles of the waste hierarchy, the polluter pays principle, as well as the concept of extended producer responsibility.

Construction and demolition waste represents one of the largest single waste stream in Serbia. Consequently, its effective governance directly determines national recycling performance and progress toward CE targets. In response to these structural pressures, Serbia adopted the Regulation on the Method and Procedure for the Management of Construction and Demolition Waste (Official Gazette RS, No. 93/2023, 2023). The Regulation transforms the construction sector from a linear “build–demolish–dispose” model into a circular “reuse-recycle oriented” model. It mandates that materials such as concrete, bricks, tiles, and asphalt must be processed and reused in the construction of roads or new facilities instead of being discarded. Contractors are now obliged to separate metal, wood, plastic, and hazardous waste (such as asbestos) directly at the construction site, which enables clean recycling streams. A Waste Management Plan is mandatory, as no structure (larger than 200 m²) can obtain an occupancy permit without proof of where the waste generated during construction has been disposed of.

In addition to construction waste, official reports indicate that packaging waste represents a significant fraction of total waste generation. This category is generated on a daily basis and, from a technical perspective, represents the most viable fraction for recycling due to its relative homogeneity and the availability of proven processing technologies. Consequently, to address this potential, Serbia has enacted the Law on Packaging and Packaging Waste (*Official Gazette RS*, No. 36/2009, 95/2018, 2018), complemented by essential secondary legislation—most notably the Regulation on the Adoption of the Packaging Waste Reduction Plan for the Period 2025–2029 (Government RS, 2025). These instruments have been meticulously developed in alignment with the European Union's Packaging and Packaging Waste Directive, signaling a strategic commitment to harmonizing domestic practice with international environmental standards. In contrast to previous regulatory periods, the Plan introduces specific and separate recycling targets for packaging waste originating directly from households (municipal waste streams), rather than focusing exclusively on industrial sources. The adoption of this Plan is considered a key step toward the establishment of a deposit return system in Serbia. It further defines precise annual recycling targets per year (Table 6) and

for the major packaging materials — paper/cardboard, plastics, glass, metals, and wood — to be achieved by 2029, as presented in Table 7 below.

Table 6

General Recycling Targets (Government RS, 2025)

Year	2025	2026	2027	2028	2029
Recycling (%)	60	62	63	64	65

Table 7

Specific Recycling Targets by Packaging Material (Government RS, 2025)

Packaging Material	2025		2026		2027		2028		2029	
	Total	Municipal								
Paper/Cardboard (%)	72	12	74	13	76	14	78	15	80	16
Beverage Cartons (Multi-layer) (%)	—	—	—	—	20	1	20	1	20	1
Plastics (%)	37	8	42	11	43	12	47	20	50	23
Polyethylene (%)	—	—	—	—	20	1	20	1	20	1
PET Beverage Bottles (%)	—	—	—	—	40	40	80	80	90	90
Other Plastics (%)	—	—	—	—	6	1	6	1	6	1
Glass (%)	49	17	50	18	52	19	53	20	54	21
Metal (%)	45	1	46	2	47	3	48	3	54	5
Wood (%)	25	0	26	0	27	0	28	0	29	0

The differentiated targets demonstrate a policy shift toward strengthening municipal packaging waste recovery, particularly through deposit return mechanisms and material-specific recycling obligations, with plastics and PET bottles identified as priority streams.

In addition to the aforementioned legal instruments, Serbia has adopted numerous rulebooks that establish detailed operational guidelines and technical standards for recycling. The Table 8 presents only the most relevant among them.

Table 8*Serbian rulebooks for specific waste streams recycling*

Name of Rulebook	Scope	Aims
Rulebook on Waste Categorization and Testing (“Official Gazette of the RS” No 56/10, 2010)	Establishes criteria and procedures for waste classification, identification of hazardous properties, and laboratory testing methods.	Ensures proper identification of waste streams, enables safe and lawful recycling processes, and prevents contamination of secondary raw materials
Rulebook on Waste Electrical and Electronic Equipment – WEEE (Official Gazette of the RS” No 99/10, 2010)	Prescribes the list of electrical and electronic products, measures prohibiting or restricting the use of electrical and electronic equipment containing hazardous substances, as well as the methods and procedures for the management of waste electrical and electronic products.	Promotes the reuse, recycling, and other forms of recovery of such waste, as well as the reduction of waste disposal.
Rulebook on Batteries and Accumulators (“Official Gazette of the RS” No 86/10, 2010)	Prescribes the content and appearance of markings on batteries, button cells, and accumulators according to the content of hazardous substances, as well as the methods and procedures for the management of waste batteries and accumulators, including equipment containing built-in batteries and accumulators.	Promote the development of new treatment and recycling technologies, as well as cost-effective recycling methods for all types of batteries and accumulators
Rulebook on Fluorescent Tubes (“Official Gazette of the RS” No 97/10, 2010)	Regulates separate collection, storage, transport, and treatment of waste fluorescent tubes containing mercury.	Ensures safe removal of mercury prior to recycling, preventing contamination of recyclable materials and enabling lawful recovery of glass and metals.
Rulebook on PCB Waste (“Official Gazette of the RS” No 37/11, 2011)	Regulates identification, storage, treatment, and disposal of waste containing polychlorinated biphenyls (PCB)	Prevents contamination of recyclable waste streams and ensures safe handling of hazardous components prior to recycling processes.
Rulebook on Titanium Dioxide Waste (“Official Gazette of the RS” No 01/12, 2012)	Regulates the management, treatment, discharge limits, and environmental monitoring of waste generated in titanium dioxide production.	Ensures safe handling of potentially hazardous industrial waste, preventing contamination of recyclable waste streams and enabling controlled recovery where technically feasible.

The primary distinction between the European Union and Serbian waste management frameworks no longer lies in their formal legislative structure, but rather in the level of implementation, institutional capacity, and infrastructural development. The EU has established a comprehensive system that includes binding quantitative recycling targets, strict landfill reduction obligations, advanced Extended Producer Responsibility (EPR) schemes, and increasingly digitalized waste-tracking mechanisms. Enforcement is

further reinforced through supranational oversight by the European Commission and the Court of Justice of the European Union.

Although Serbia has largely harmonized its legal framework with the EU *acquis*, limited financial resources, insufficient municipal infrastructure, historical reliance on landfill disposal, and fragmented local governance structures continue to hinder full operational alignment with EU standards (Isakovic *et al.*, 2024). Nevertheless, recent developments indicate progress. The strengthening of EPR systems, gradual establishment of regional waste management centers, deeper integration of CE principles into national policy, and ongoing regulatory harmonization demonstrate forward momentum. Comparative assessments of Western Balkan countries frequently identify Serbia as advancing in legislative convergence, despite persistent implementation gaps (Belis *et al.*, 2024).

8 CONCLUSION

The ecosystem is strained by the ongoing use of resources. Accordingly, waste management has drawn more attention from the perspective of a circular economy. Sustainable development, which is impacted by a variety of factors, including the condition of the living environment, has received a lot of attention lately.

Recycling, avoiding debris, and reducing landfill deposition are the main goals of this industrial area, while the goal of a CE is to take into account the enduring value of products and resources. These facts mean that after a resource's life cycle is complete, it should be reused to produce new value. The numerous waste to energy systems deployed worldwide for solid waste obtaining energy are reported in this paper. The composition and properties of waste are essential for determining the best waste to energy method. A resurgence of interest in bioeconomy and biorefineries is anticipated to lead to the development of numerous innovative techniques for resource recovery.

Sustainable waste management seeks to reduce the amount of waste discharged entering the surroundings by reducing the amount of waste developed. Future generations must continue to live in a varied and healthy environment. At the national and international levels, achieving this aim is closely and immediately related to raising environmental consciousness and reducing negative externalities. Further improvement

of recycling infrastructure and public awareness campaigns are essential to increase waste separation rates at the source. Strengthening cooperation between governmental institutions, the private sector, and citizens can significantly contribute to achieving long-term sustainability goals.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

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