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Cadmium and lead flow analysis as a decisions support data for waste management

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Abstract: Striving for EU membership, the Republic of Serbia must adjust its waste management practices to comply with EU directives, including targets to reduce biodegradable waste disposal in landfills, as outlined in its Waste Management Program 2022–2031. Cadmium and lead, two highly toxic heavy metals, that are present in municipal solid waste, can pose high environmental and human health threats if not properly managed. The research evaluates how different technologies for biodegradable waste treatment influence the transformation of cadmium and lead flows through waste management systems. Hence, two waste management scenarios were modelled and developed for the Republic of Serbia, where the flows of cadmium and lead are monitored. The results indicate the differences between quantities and concentrations of cadmium and lead emitted in environmental media, thus confirming the various impacts of different waste technologies on achieving the vital goal of waste management – protection of the human health and the environment. The research concludes the crucial role of the versatile approach, where the quality of waste management outputs is highlighted.

Keywords: heavy metals; materials; quality; flow scenarios; substance flow analysis.

INTRODUCTION

The importance of the quantitative aspect has been defined – the greater the amount of waste removed from natural habitats, the greater the benefits for both human health and the environment.[1] Nevertheless to achieve effective, goal-oriented waste management an equal emphasis on both quality and quantity of waste management is fundamental.[2,3] It is crucial to treat waste in a way that pro-

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tects the environment and human health, since even small amounts of hazardous substances can have serious adverse short and long term effects.[1] From the waste to resource point of view, the impurities in the circular waste management system can significantly affect the re-use of waste as a resource. This indicates the need for the approach that is also oriented towards understanding the vital substances through waste management systems. Hence, two waste management scenarios were developed for the Republic of Serbia, where the flows of cadmium and lead are monitored.

Republic of Serbia, in its capacity as a candidate country for European Union (EU) membership, is anticipated to adopt solid waste management strategies that align with the directives established by the EU. According to the Waste Management Program of the Republic of Serbia for the period 2022–2031, the target values for reducing the disposal of biodegradable waste at landfills are defined.[4] The specific objective is to reduce the disposal of biodegradable waste in landfills by 75 % of the total amount generated in 2008 by the year 2028. The ultimate goal is to reach a 50 % reduction by the end of 2032 and a 35 % reduction by the end of 2039. The Program envisions the construction of a comprehensive biodegradable waste diversion infrastructure by 2037, and it is anticipated that a significant period of adjustment will be necessary to ensure these systems operate in compliance with the established standards.

The fulfilment of the goals related to reducing the quantity of biodegradable municipal waste deposited in landfills, according to the Landfill Directive (1999/ /31/EC), does not provide insight into the quality of waste management. Hence, given the misalignment between the objectives of the directive and waste management goals, an examination was conducted to assess the impact of waste management models in accordance with the directive. More specifically, the aim was to comprehend how these models affect the core objective of waste management. The key waste management goal is inter and intra disciplinary and encompass protection of human health and the environment.[5,6] To fulfil this objective, a key focus on individual elements is essential, as they play a pivotal role in determining environmental impacts and resource potential. In the realm of waste management, effective decision-making necessitates well-defined objectives, suitable methodologies, and accurate data of known uncertainty. Having adequate and sufficient information regarding waste composition is essential to monitor and control the transformations that occur during waste treatment.[7] The background knowledge is crucial, as certain substances play a significant role in determining whether waste holds resource potential or is considered hazardous material.[8]

Cadmium and lead rank as the most toxic heavy metals, representing substantial threats to both human health and the environment. Prolonged cadmium exposure can result in a spectrum of health complications, encompassing kidney disorders, hypertension, and lung emphysema. Lead can inflict severe damage upon the central nervous system, activating a variety of symptoms, from irritability and cognitive impairment to the onset of encephalopathy.[9] Burnley has shown that implementing an integrated waste management strategy effectively diverts lead and cadmium from the environment using appropriate treatment technologies.[10] Products manufactured decades or even a century ago often contain legacy substances that are now considered toxic or banned, with cadmium and lead being the most significant among them, directing their proper management.[8] Every year, a broad spectrum of new consumer products is being introduced, marked by multiplex chemical compositions and they may include novel hazardous substances not previously utilized. The role of waste management extends beyond the provision of resources derived from waste involving handling non-useful and hazardous substances by facilitating their proper transformation and directing them toward sustainable, long-term disposal solutions.[11,12] Adequate waste management is achieved by "clean" recycling materials for substituting primary materials, inert residues suitable for safe disposal, and maintaining emissions into the environment at acceptable levels.[13]

The two original areas of material flow analysis (MFA) application are analysing city metabolism and analysis of pollutant pathways in regions. Over time, MFA has been widely adopted in various fields, such as process control, waste and wastewater treatment, agricultural nutrient management, water quality management, resource conservation and recovery and more.[14] Stanisavljevic and Brunner developed waste management scenarios that were quantitatively assessed using substance flow analysis.[15] Additionally, similar topics were addressed by Astrid *et al.*, presenting the Austrian waste management system, and Arena *et al.*, applying a substance flow analysis approach in Italian areas.[16,17] This research models two potential future waste management systems in the Republic of Serbia and applies material flow analysis and substance flow analysis (Pb and Cd) to indicate the impact on waste management goal (protection of human health and the environment). Improved waste management systems were modelled in order to monitor the future flows of heavy metals through waste management systems and to indicate how different biowaste treatment technologies influence the fulfilment of the most important waste management goal.

EXPERIMENTAL

Materials and methods

MFA, based on the fundamental principle of mass balance, is a systematic assessment of material flows and stocks within a specified system, encompassing spatial and temporal boundaries. The MFA calculations were performed using modern and sophisticated tool STAN 2.6 software.[18] Furthermore, in addition to MFA, the term substance flow analysis (SFA) is occasionally used.[14] SFA represents a type of MFA that only applies to a specific substance within a system and is based on the input flow of a substance, the flow of which can be followed through system in order to define output flows. It is a comprehensive tool for evaluation the effectiveness of a unit treatment or entire waste management system in achieving waste management goals. Information acquired through SFA is crucial for evaluating the flows of substances within the waste management system. SFA focuses on monitoring the transformations that occur to wastes during their treatment, encompassing both valuable and hazardous substances.[15]

The mass-balance principle applies to systems as well as processes. In accordance with the mass-balance principle, the total mass of inputs entering a process is equivalent to the combined mass of outputs from that process, along with a stock term accounting for the accumulation or depletion of materials within the process. It is elucidated through the following equation:

$$\sum_{ki} \dot{m}_{\text{input}} = \sum_{ko} \dot{m}_{\text{output}} + \dot{m}_{\text{stock}} \tag{1}$$

where ki – number of input flows, *ko* – number of output flows, $\dot{m}_{\text{input}}$ – mass of input flows, $\dot{m}_{\text{output}}$ – mass of output flows and $\dot{m}_{\text{stock}}$ – mass of stocks.

The sink indicator, as elucidated by Kral *et al.*, serves as a powerful tool for quantifying the proportionate mass of a specific substance considered environmentally acceptable within the framework of waste and emission flows.[11] This indicator represents the ratio between the amount of environmentally acceptable and unacceptable flows and sinks and defines the best possible scenario outcome. The innovative concept is defined on a scale ranging from 0 %, representing the worst-case scenario, to 100 %, denoting the best-case scenario. Kral *et al.* developed and provided a detailed explanation of the sink indicator concept, laying the foundation for its application in environmental assessments. The sink indicator formula is expressed as the ratio of the sum of acceptable flows to the sum of actual flows, multiplied by 100 to represent the result as a percentage:

$$\lambda = \frac{100Fa}{F} \tag{2}$$

where λ – the sink indicator (%), *Fa* – the sum of acceptable flows and *F* – the sum of actual flows.

Calculating the sink indicator requires the following information:

- The actual flows which are determined by SFA results
- The critical flows refer to the specific levels of cadmium and lead, that are considered to be of significant concern due to their potential impact on human health. In accordance with legislative values for Pb and Cd for the leachate from landfills[19] and for compost material,[20] these critical levels are defined by legislation and represent a threshold beyond which the risks are considered unacceptable. This is the level that regulatory authorities have determined to be safe for human health and the environment.
- The acceptable flows correspond to the lower of the actual flows and the critical flows.

Modelling approach

The Waste Management Program of the Republic of Serbia has set target values for reducing the disposal of biodegradable waste at landfills for various years, including 2028 and 2032. However, it is in 2039 that the program likely envisions achieving a substantial level of compliance with EU standards, suggesting that a more extended period of adjustment is needed to ensure the proper operation of waste allocation systems in accordance with EU requirements. Consequently, the year 2039 is chosen because it represents a significant milestone in the Republic of Serbia's efforts to align its solid waste management strategies with EU directives.

The research input data structure was defined by the analysis of the current state and the calculated projections of municipal solid waste (MSW) amounts and the content in the Republic of Serbia.[21] A data-based prediction of municipal solid waste production for the year 2039 is estimated to be approximately 3.5 Mt. The input data for substance concentrations in waste fractions were modified and applied according to Stanisavljevic, Astrid *et al.* and Arena *et al.*[16,17,22] Mass flows and comprehensive data on the presence of the heavy metals Pb and Cd within different waste components are presented in Table I.

TABLE I. Mass flows and substance flows (for lead and cadmium) in the input data

Input fractions	Mass flow, t year^{-1}	Cadmium flow, mg kg^{-1}	Lead flow, mg kg^{-1}
Biodegradable waste[a]	1,220,000	1.05	15.05
Paper and cardboard	415,000	1.95	14
Glass	300,000	1.4	215
Metal	105,000	6.6	1437
Plastic	600,000	22.5	213
Other[b]	840,000	22,3	323
Total/average	3,480,000	10.2	184

[a]garden, kitchen and green; [b]textiles, leather, diapers, batteries, fine elements, *etc*.

Based on comprehensive information from other studies, electronic waste, batteries and plastic are identified as primary contributors to the sources of Cd, while metals, primarily, and electronic waste and plastics to a lesser extent, are highlighted as the primary contributors to sources of Pb. While the concentrations of cadmium and lead in biodegradable waste are relatively low, with values of 1.05 mg kg^{-1} for Cd and 15.05 mg kg^{-1} for Pb, it's essential to acknowledge that these levels are not insignificant and warrant attention due to their potential environmental impact.

Scenarios development

Waste management consists of several functional units: waste generation, collection and transport, pre-treatment and treatment and waste disposal. The systems are limited in time and space, where consumer goods are defined as input into the system and become waste at the end of their life cycle. Emissions to air, water and soil after waste treatment and final disposal, compost after treatment of the biodegradable part of waste and recycling materials are defined as outputs of the system. A simplified graph of the scenarios by functional units is shown in the Fig 1.

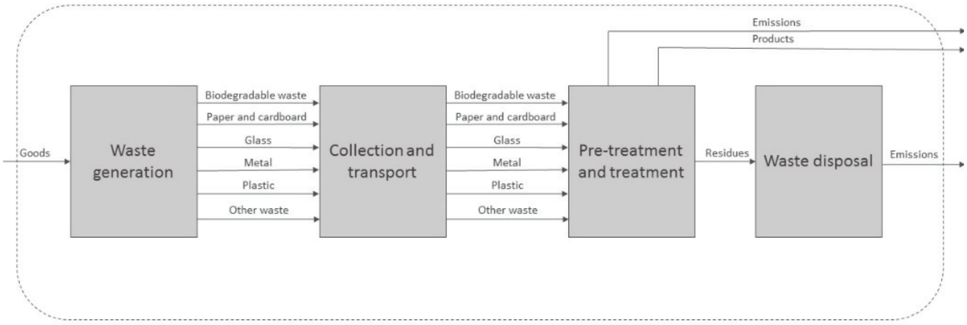

Fig. 1. Simplified representation of waste management system.

The developed waste management systems observe and compare how different ways of treating municipal solid waste affect waste management objectives. Two scenarios are outlined in the following sections.

Scenario I. Generated municipal solid waste is divided into following categories: biodegradable waste, paper and cardboard, glass, metal, plastic and other. Households utilize a three-bin system to separate MSW, comprising recyclable materials, wet waste and residual waste collections. In this case, separately collected wet waste is subjected to composting treatment processes, aimed at enhancing its environmental sustainability. Recyclable materials, upon collection, are omitted from the scope of this study as they no longer represent waste, but valuable resources for potential utilization in diverse recycling procedures. The remaining waste stream, unallocated to either recyclables or wet waste bins, is directed towards disposal in a sanitary landfill, indicating the management of non-recyclable and non-compostable waste components. Residues resulting from the composting treatment procedure are also deposited into the sanitary landfill.

Scenario II. This scenario with regard to the treatment of waste, compared to the previous scenario, primarily diverges in the treatment technology applied to wet waste. In this scenario, separately collected wet waste undergoes anaerobic digestion with subsequent post-composting as a distinct treatment process. Following the post-composting stage, any remaining residues are consigned to a sanitary landfill. The inclusion of Scenario II serves to emphasize the opposing approaches between composting and anaerobic digestion technologies in the context of wet waste treatment.

Transfer coefficients of the selected waste treatment processes describe the partitioning of a substance in a process and are defined for each output result. The most suitable transfer coefficients for the modeled scenarios were synchronized and set through the literature assessment. Data on the mass and substance balance for the composting process were derived from Allesch and Brunner, information regarding the landfill was obtained from Stanisavljevic *et al.*, while detailed data on anaerobic digestion process are presented by Jensen *et al.*[15,16,23]

RESULTS AND DISCUSSION

Material flow analysis and substance flow analysis were applied to the previously described scenarios. Modelled scenarios for cadmium and lead flows are presented below in Figs. 2–5.

Values and concentrations of the observed heavy metals in various environmental mediums are presented in Tables II and III.

The concentration values of cadmium and lead in the obtained compost material were compared with the limit values of the Serbian standards.[20] The Serbian standard for compost has set the concentration values for Cd and Pb to 1.5 and 200 mg kg^{-1}, respectively. The compost reuse for Cd has shown in both scenarios' higher concentrations that the given standard limitations. The Pb is in both scenarios in compliance within standard. Due to differences in the functioning of the composting and anaerobic digestion processes, there are differences in the distribution of Cd and Pb into the environmental compartments. Considering scenarios results, it is evident that Cd and Pb concentration values are lower in the process of composting than after anaerobic digestion. Cadmium and lead concentration values in landfills body show similar results in both scenarios.

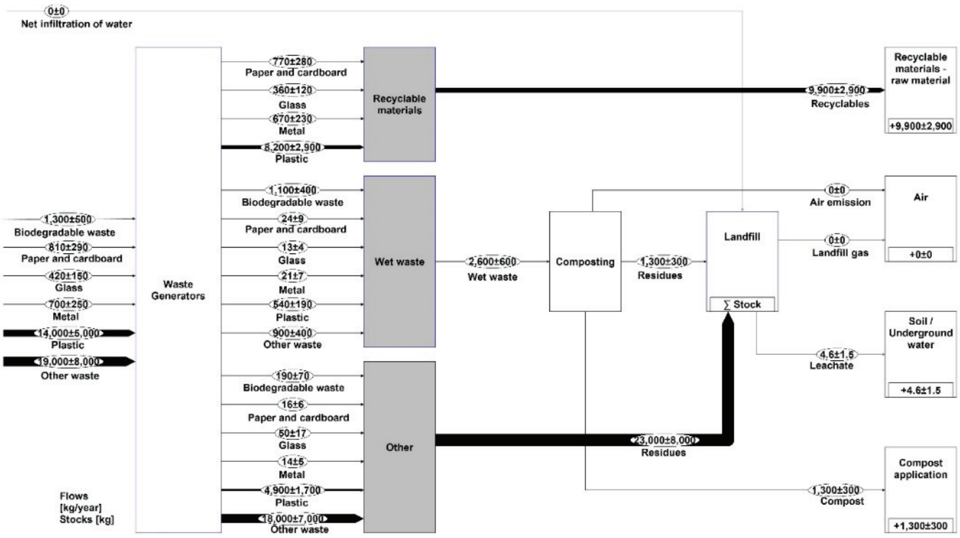

Fig. 2. Cadmium flow for Scenario I.

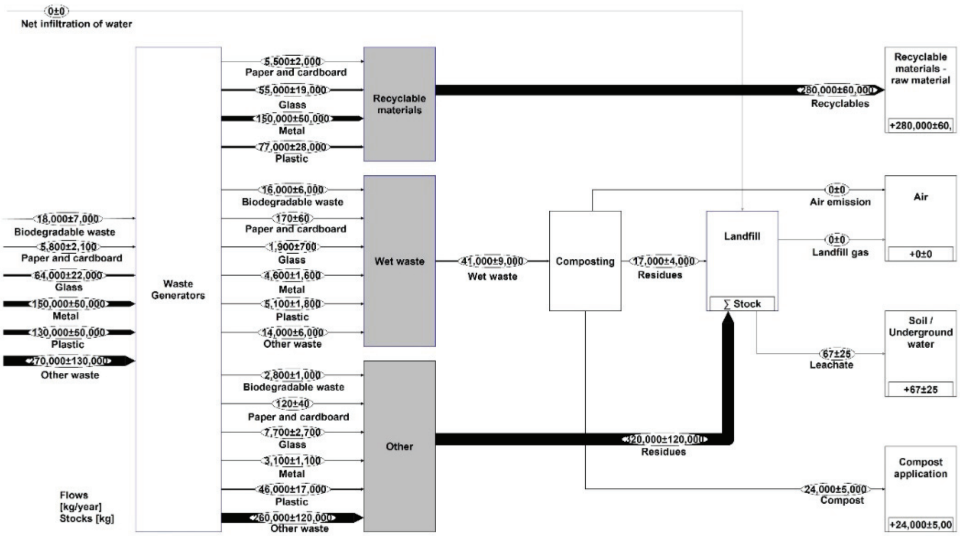

Fig. 3. Lead flow for Scenario I.

The high concentrations of heavy metals are sign of compost contamination and indicators of the potential environmental risks. Depending on the specific context and the levels of contamination, certain use of compost is possible for soil stabilization, landfill cover, remediation and landscaping.

While the mass balance for the scenarios includes emissions to air, soil and water, substance flow analysis reveals that Cd and Pb ultimately end up in compost and soil/underground water only. Heavy metals such as Cd and Pb undergo transformations, making them less mobile or volatile, thus preventing their release into the air. Emissions into the soil are slightly higher in scenario I.

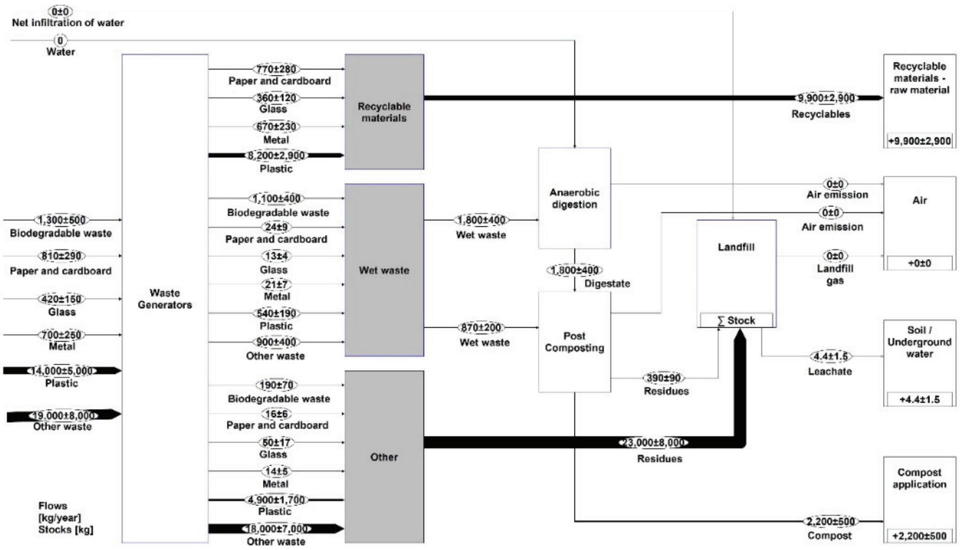

Fig. 4. Cadmium flow for Scenario II.

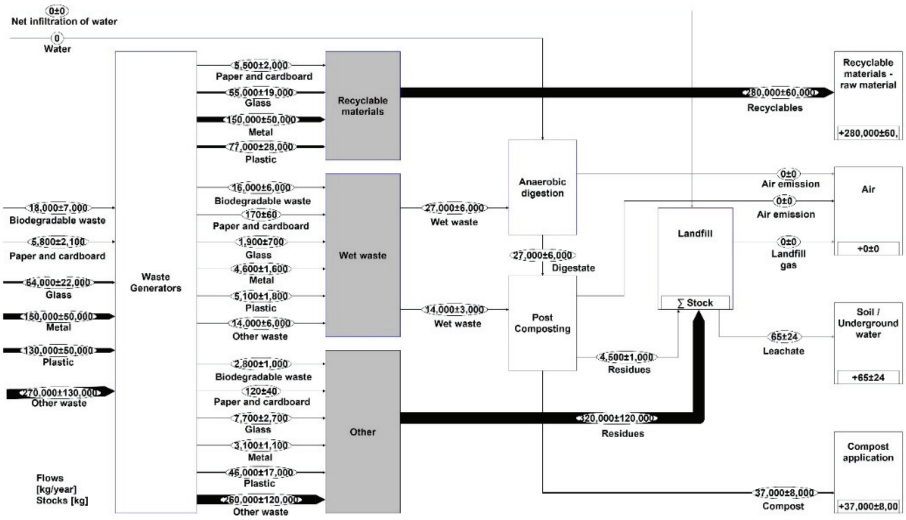

Fig. 5. Lead flow for Scenario II.

The composting scenarios presented in this study are largely consistent with previous studies.[24,25] Zarkadas *et al.*'s research yielded slightly superior outcomes for heavy metals, since the collection was focused on biodegradable food waste. Enhancing the biodegradable waste collection process and minimizing impurities introduced into the system can lead to improved results. Knoop *et al.*'s results also demonstrated similar concentrations of cadmium and lead after the anaerobic digestion process. [26] The study by Arena *et al.* presents comparable results for mass flow analysis, with no specific information on substance concentrations after the anaerobic digestion process. [17]

TABLE II. Values of Cd and Pb in environmental compartments expressed in kg year^{-1}

Environmental compartments	Scenario I		Scenario II	
	Cd	Pb	Cd	Pb
Air	0	0	0	0
Soil/underground water	4.6	67	4.4	65
Soil (compost reuse)	1300	24000	2200	37000
Landfill body	24000	340000	23000	320000

TABLE III. Concentrations of Cd and Pb in environmental compartments expressed in mg kg^{-1}

Environmental compartments	Scenario I		Scenario II	
	Cd	Pb	Cd	Pb
Air	0	0	0	0
Soil/underground water	0.01	0.08	0.01	0.08
Soil (compost reuse)	3.23	59.56	4.89	79.91
Landfill body	39.88	549.67	39.05	538.75

Sink indicator

The quantification of the sink indicator yielded the results depicted in Fig. 6.

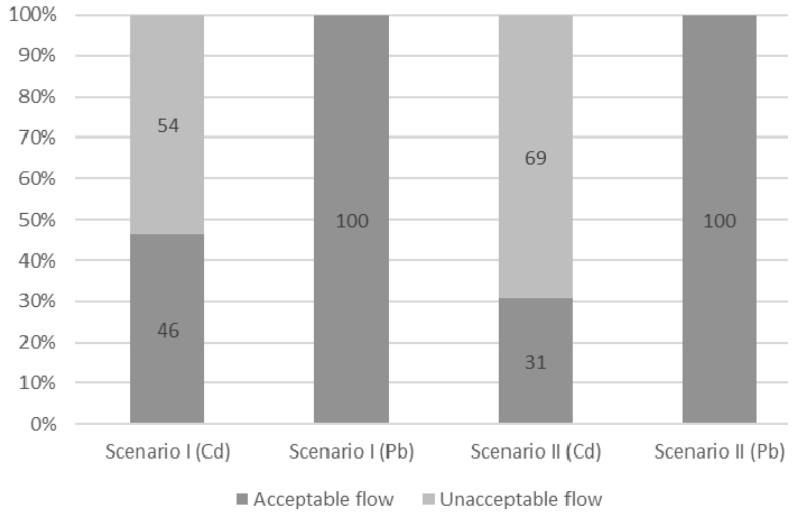

Fig. 6. Sink indicator results expressed in percentages.

The results for Pb indicated that in both scenarios, concentrations remained within the limit values (100% directed to the acceptable sink), due to the high allowable values of lead concentrations.

Analysing the modelled scenarios and Cd values within the anaerobic digestion context, 30.68 % of the input material is characterized as an acceptable flow. In the case of the composting process, 46.39 % is designated as an acceptable flow. These findings indicate a greater proportion of the input material undergoes a satisfactory transformation or stabilization during composting when compared to anaerobic digestion. Unacceptable levels arise from elevated cadmium concentrations in compost material, with the outcomes once again underscoring superior results achieved through the composting process.

CONCLUSION

Understanding the influence of the transformation of materials within waste management systems and how the specific application of various technologies in these systems can impact material transformation, directing substances to different sinks, is essential. All transformations within the system are based on the mass conservation law. The mass-balance principle applies to systems as well as processes. In accordance with the mass-balance principle, the total mass of inputs entering a process is equivalent to the combined mass of outputs from that process, along with a stock accounting for the accumulation or depletion of materials within the process. The material entering the system transforms into other forms and will definitely remain, it will not disappear. According to this law, the material entering the system undergoes transformation into different forms and is assured to persist rather than vanish.

Fulfilling the objectives linked to decreasing the quantity of biodegradable municipal waste disposed of in landfills, according to the Landfill Directive (1999/31/EC), doesn’t provide insights into the impact on the main environmental compartments: atmosphere, hydrosphere and lithosphere. The emphasis is on recognizing the significance of considering waste management goals. Thus, a more comprehensive knowledge base for waste management development can be established.

The emissions of hazardous heavy metals, cadmium and lead in two modelled scenarios designed for the Republic of Serbia waste management systems provide us with a clearer insight into the quality-level waste management goals. There is no feasible means to reduce the amounts of Pb and Cd in waste flows. Nevertheless, through the application of suitable technologies, these heavy metals can be directed into appropriate final sinks to protect human health and the environment. Designed scenarios both show increased values of Cd, while the values of Pb are in accordance with Serbian legislative. Observation of the obtained data for lead indicates that limit values for lead are very high, and necessity for it to be more strictly determined. Final modelled values distinguish Scenario I as better solution concerning share of cadmium and lead in possible waste management system. Importance of waste management system modelling perceives the possible pollution hotspots and allows for additional treatment to be introduced in structure, creating clean circular economy blueprint.

The results emphasize that cadmium and lead values and concentration levels need to be perceived separately. Total values of processed waste are considered to be key factor in waste management systems. The modelled data indicates that different approach should be taken into consideration, whereas concentration values are to be observed. The new approach is backed with the fact that some metals can have very adverse effect on both population health and the environment even in small doses, especially in long term exposure. The application of the MFA and SFA approaches has the potential to provide positive benefits for understanding cadmium and lead contamination, thereby decreasing the toxic hazard’s impact on human health and the environment in the future waste management systems of the Republic of Serbia. Concerning the study's limitations and potential avenues for further research, modelling scenarios for additional substances would be advantageous. Future research should prioritize identifying critical and problematic substances, analysing their impact on waste management goals. Furthermore, this study did not explore the influence of Cd and Pb on the implications of the recycling process. Subsequent research could address this aspect, providing a more precise assessment of substance flows associated with the implementation of recycling technologies.

ИЗВОД

АНАЛИЗА ТОКОВА КАДМИЈУМА И ОЛОВА КАО ПОДРШКА ПОДАЦИМА ЗА УПРАВЉАЊЕ ОТПАДОМ

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Као део процеса тежње ка чланству у ЕУ, Република Србија мора прилагодити своје праксе управљања отпадом како би се ускладила са директивама ЕУ, укључујући циљеве смањења одлагања биоразградивог отпада на депоније, како је дефинисано у Програму управљања отпадом. Кадмијум и олово, два високо токсична тешка метала који се налазе у комуналном чврстом отпаду, могу представљати велике претње по животну средину и људско здравље ако се са њима не управља правилно. Истраживање приказује како различите технологије за третман биоразградивог отпада утичу на трансформацију токова кадмијума и олова кроз системе управљања отпадом. Стога су развијена и моделована два сценарија управљања отпадом за Републику Србију, где су праћени токови кадмијума и олова. Резултати указују на разлике између количина и концентрација кадмијума и олова емитованих у животну средину, потврђујући тако различите утицаје примењених технологија на постизање циљева управљања отпадом. Као резултат истраживања истиче се неопходност свестраног приступа, са нагласком на квалитет излазних токова приликом управљања отпадом.

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