



DEVIATIONS BETWEEN TIER 1 AND TIER 2 ESTIMATES OF METHANE EMISSIONS FROM SERBIAN LANDFILLS: ANALYSIS OF IPCC FOD MODEL APPLICATION (2021–2024)

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Abstract

Introduction: Methane (CH₄) emissions from landfills are estimated in national inventories using the IPCC First-Order Decay (FOD) model. Two methodological tiers exist: Tier 1, based on population data and default parameters, and Tier 2, based on measured waste quantities and locally determined parameters. The Republic of Serbia landfills over 90% of its municipal waste, yet the magnitude of methodological deviation between Tier 1 and Tier 2 estimates remains unquantified. **Methods:** Annual CH₄ emissions from 12 Serbian sanitary landfills (2021–2024) were estimated using both the IPCC Tier 1 and Tier 2 FOD approaches. Tier 1 employed effective population data (0.95 kg/capita/day) and default parameters (DOC=0.15, MCF=1.0, k=0.05 yr⁻¹). Tier 2 used measured waste quantities from the Serbian Environmental Protection Agency (SEPA) and locally determined parameters (DOC=0.1037–0.1085, MCF=0.5–1.0, k=0.06 yr⁻¹). Relative deviations between the two approaches were calculated and analysed statistically. **Results:** The Tier 1 approach systematically overestimated emissions by a weighted average of 42.7 ± 11.3% compared to Tier 2. The largest deviation occurred at the Vinča landfill (67.2%), where a waste-to-energy (WtE) plant and reduced methane correction factor (MCF=0.5) significantly lower emissions. The Subotica landfill showed a 38.5% deviation (MCF=0.5). Vinča alone contributes approximately 65% of national CH₄ emissions from the sanitary landfill sector. **Conclusion:** The continued application of Tier 1 methodology introduces significant, systematic overestimation of methane emissions from Serbian landfills. Transitioning to Tier 2 approaches with measured waste data and locally calibrated parameters is essential for accurate national greenhouse gas inventories, effective mitigation planning, and alignment with EU climate obligations.

1. Introduction

Municipal solid waste landfills represent a significant source of methane (CH₄), a greenhouse gas with a global warming potential (GWP) 28 times greater than CO₂ over a 100-year horizon [1]. According to recent estimates, the waste sector contributes 5–10% of global anthropogenic CH₄ emissions, with landfills being the dominant source [2]. In the Republic of Serbia (RoS), despite efforts to modernize the waste management system, over 90% of municipal waste is still landfilled [3].

The Intergovernmental Panel on Climate Change (IPCC) developed the First-Order Decay (FOD) model for estimating CH₄ emissions from landfills, which has become the global standard for national greenhouse gas inventories [4]. The model is applied at three levels of complexity: Tier 1 (population data, average waste generation rates, and default

IPCC parameters), Tier 2 (measured waste quantities and adjusted parameters), and Tier 3 (dynamic models and direct measurements) [4]. Recent studies indicate that the application of default parameters (Tier 1) in specific local conditions can lead to significant estimation errors [5, 6].

It is important to note that Tier 1 and Tier 2 methodologies are not directly comparable in terms of precision but rather represent different levels of complexity within the IPCC hierarchical approach [4]. While both approaches provide emission estimates, Tier 1 uses basic, globally default data, which can lead to higher uncertainty and systematic overestimation of emissions, especially in specific local conditions. Conversely, the Tier 2 approach uses measured activity data and locally determined parameters, enabling a

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more accurate assessment that better reflects national circumstances [4, 7]. Therefore, the comparison of these two approaches, as conducted in this study, serves not to determine a 'more accurate' method (which is by definition Tier 2), but to quantify the methodological uncertainty and systematic error arising from the use of default parameters in the context of Serbia.

In Serbia, official emission inventories use data from the Serbian Environmental Protection Agency (SEPA) based on measured waste quantities (Tier 2 approach). However, in scientific literature and preliminary analyses, Tier 1 estimates based on population data are often used. The aim of this study is to quantify and analyze the deviations between Tier 1 and Tier 2 approaches in estimating CH₄ emissions for 12 sanitary landfills in Serbia for the period 2021-2024, using official measured SEPA data and locally determined parameters for each landfill [8]. Special focus is placed on identifying the causes of deviations and the implications for the accuracy of national emission inventories.

Additionally, global studies show that landfills in transition economies like Serbia have lower waste degradation rates due to drier climates and improved management, leading to lower actual emissions compared to default models [9].

2. Materials and Methods

2.1. IPCC FOD Model – Tier 2 Approach

For estimating annual CH₄ emissions, the IPCC FOD model was used in its full summation form, which takes into account the age structure of deposited waste (waste-in-place), in accordance with the IPCC 2006/2019 methodology [4]. The amount of methane generated in year t is calculated as:

$$\frac{CH_4(t)}{MCF \cdot F \cdot \frac{16}{12}} = \sum_x MSW_x \cdot DOC \cdot DOC_f \cdot (e^{-k(t-x)} \cdot (1 - e^{-k})) \quad (1)$$

where:

- MSW_x – mass of waste deposited in year x (Mg),
- DOC – degradable organic carbon fraction,
- DOC_f – fraction of DOC that degrades (default = 0.5),
- MCF – methane correction factor,
- F – fraction of methane in landfill gas (default = 0.5),
- k – decay rate constant (year⁻¹),
- 16/12 – molecular weight ratio CH₄/C (1.3333),
- e^{-k(t-x)} – remaining fraction of waste from year x ,
- (1-e^{-k}) – fraction degraded during year t .

The oxidation factor (OX) was not included (OX = 0), in accordance with IPCC recommendations for active and young sanitary landfills without a stable final cover layer. All relevant data on deposited waste quantities from the beginning of each landfill's operation were used.

The DOC value for each landfill was determined based on the estimated morphological composition of waste and IPCC default values for individual fractions [4], according to the formula:

$$DOC = \sum (P_i \times DOC_i) \quad (2)$$

where:

- P_i is the proportion and

DOC_i is the default DOC value for the i -th waste fraction (e.g., paper and cardboard 6.2%, biodegradable waste 45.2%, textile 3.5%) [6].

2.2. Assessment Approaches

In accordance with the IPCC methodology hierarchy, Tier 1 represents the basic level using globally default factors and available national statistical data, while Tier 2 requires the use of country specific data and parameters, enabling a more sophisticated and accurate assessment [4, 7]. The approaches differ both in the sources of activity data and in the values of the parameters used (e.g., DOC, MCF, k), which directly affects the final emission estimate.

2.2.1. Tier 1 Approach

In this paper, the Tier 1 approach was implemented as an improved estimate aiming to mitigate the limitations of using only national aggregate data. The annual amount of municipal solid waste (MSW_t) for each landfill was calculated based on the effective population served by the landfill, rather than the total national population. The effective population for each of the 12 sanitary landfills was determined according to official waste management planning documents [10].

MSW for Tier 1 for each landfill and each year t was calculated according to the formula:

$$MSW_{T1,i}(t) = P_{eff,i} \times r_{gen} \times 365/1000 \quad (3)$$

where:

- P_{eff,i} = effective population served by landfill i (inhabitants),
- r_{gen} = average municipal waste generation rate (0.95 kg/capita/day), according to 3; [3, 4].

The annual waste quantities thus obtained were used as input to the IPCC FOD model (Equation 1). The following default IPCC parameter values for temperate climate were used [4]:

DOC = 0.15; DOC_f = 0.5; MCF = 1.0; F = 0.5; k = 0.5 * 0.12 = 0.06 yr⁻¹

Important methodological limitation: Although the use of effective population represents an improvement over using total national population, this approach cannot fully represent the actual amount of waste at the landfill. It assumes that 100% of waste generated by the effective population is disposed of at that sanitary landfill, which ignores the existence of non-sanitary landfills and the fact that part of the population is not covered by organized waste collection [11]. Therefore, even this improved Tier 1 approach can systematically overestimate MSW, consequently leading to overestimated emissions compared to the Tier 2 approach based on measurements.

2.2.2. Tier 2 Approach

Building upon the methodological framework of the first level, the application of the Tier 2 approach enabled a more detailed and accurate emissions estimate, based on site-specific data. The foundation of this approach consists of measured annual waste quantities, obtained from the official database of the Serbian Environmental Protection

Agency [12] for each of the twelve sanitary landfills included in the study.

To align the assessment more closely with actual field conditions, locally determined parameters were utilized instead of default values from guidelines. These values, encompassing the methane correction factor (MCF) and the degradable organic carbon content, are presented in Table 1 and are derived from available studies and SEPA data.

Special methodological attention was given to the "Vinča" landfill, which is distinguished by specific conditions arising from its integration with a waste-to-energy (WtE) incineration plant. To realistically represent the altered degradation conditions following the commissioning of the WtE facility [9], two key corrections were applied in the assessment. First, a reduced MCF of 0.5 was adopted, accounting for the combined effect of a decreased inflow of biodegradable waste, active landfill gas management, and changed conditions within the landfill body. Second, the annual quantities of municipal solid waste ultimately disposed of at the landfill were corrected by applying a factor of 0.7818. This factor precisely reflects the proportion of waste that still ends up in the landfill after treatment at the WtE facility.

2.3. Data Sources

The reliability and transparency of the conducted emission assessment rest upon carefully selected and verified data sources. The quantitative foundation of the research is based on measured waste quantities, obtained from the database of the Serbian Environmental Protection Agency [12]. This database includes annual data for twelve sanitary landfills in the RoS for the period 2021–2024, as well as historical time series since the commencement of operations at each individual landfill. For the Vinča landfill, data in the database are available from 2021 onwards, which corresponds to the start of operations of the new landfill complex with the waste-to-energy (WtE) plant, while for the other landfills the time series begin in 2015. For the Vinča landfill, in addition to data from the SEPA database for the period 2021–2023, the estimated waste quantity for 2024 was taken from a media report [13], as the official data for that year were not yet finalized at the time of the study.

The demographic framework for estimating the served population was defined based on the official results of the 2022 Census of Population, Households and Dwellings, conducted and published by the Statistical Office of the RoS [14]. Finally, the location-specific parameters, which form the core of the Tier 2 analysis and relate to waste composition and landfill conditions, are systematized in Table 1. These data were collected from targeted studies of individual landfills, supplemented and cross-verified with relevant SEPA databases. Furthermore, for the purposes of the Tier 1 approach, data on the effective population covered by waste collection services for each sanitary landfill were taken from the strategic document "Waste Management Program in the RoS for the period 2022–2031" [10].

2.4. Statistical Analysis and Uncertainty Analysis

To ensure comparability with relevant studies and international reports, all estimated methane emissions are

expressed in kilograms of carbon dioxide equivalent (kg CO₂e). The conversion utilized a global warming potential (GWP) for methane of 28, based on the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [1]. To quantify the differences between the applied methodological tiers, the relative deviation between estimates obtained using the Tier 1 and Tier 2 approaches was calculated according to the following formula:

$$\text{Relative deviation}(\%) = \left[\frac{(\text{Tier1} - \text{Tier2})}{\text{Tier2}} \right] \times 100 \quad (4)$$

Basic statistical parameters, including mean values, standard deviations, and 95% confidence intervals, were calculated for each individual landfill, as well as for the weighted average of all twelve landfills. Given the relatively short time series of available annual data ($n = 4$), confidence intervals were determined using Student's t-distribution with $n-1$ degrees of freedom. Consequently, these intervals should be interpreted primarily as indicative measures of uncertainty rather than strict statistical bounds. All calculations were performed in the R programming environment, version 4.3.1, employing base statistical functions.

In addition to quantitative statistical processing, a qualitative analysis of uncertainty sources was conducted in accordance with IPCC guidelines [4]. The following key factors contributing to the overall uncertainty of the emission estimates were identified:

- Uncertainty in waste quantity (MSW): Although based on operational weighbridge data, the uncertainty is estimated at ± 5 –10%, due to potential record-keeping discrepancies and weighing variations.
- Uncertainty in the DOC parameter (degradable organic carbon): Variability in waste composition over time and across landfills, along with the use of default values, introduces an uncertainty of approximately $\pm 20\%$.
- Uncertainty in the k parameter (decay rate): Its dependence on local climatic conditions (precipitation, temperature) and waste composition leads to a higher level of uncertainty, estimated at $\pm 30\%$.
- Uncertainty in the MCF parameter (methane correction factor): Subjective judgment regarding landfill management conditions, particularly in cases with active gas collection systems or altered degradation regimes (e.g., the Vinča landfill), results in an uncertainty range of ± 0.1 to 0.2 .

3. Results

For the application of the Tier 2 approach, it is necessary to use locally determined parameters that reflect the specific conditions at each landfill. Table 1 shows the measured waste quantities (MSW_{*i*}) for the period 2021–2024 and the local parameter values (DOC, MCF, k) used for each of the 12 analyzed sanitary landfills. These parameters, taken from studies and the SEPA database, are crucial for a more accurate emission estimate compared to default IPCC values.

Table 1. Local Parameters Used in Tier 2 Calculations

Landfill	MSW _i (measured, 2021-2024)	DOC	MCF	k (year ⁻¹)	Activity period
RSD „Duboko" Užice	87.905-35.328 t	0.1037	1.0	0.06	2015-2024
RSD „Vrbak" Lapovo	50.404-25.132 t	0.1037	1.0	0.06	2015-2024
RSD Kikinda	29.717-21.937 t	0.1037	1.0	0.06	2015-2024
RSD „Gigoš" Jagodina	75.835-97.846 t	0.1037	1.0	0.06	2015-2024
RSD „Željkovac - D2" Leskovac	77.388-85.060 t	0.1037	1.0	0.06	2015-2024
RSD „Muntina padina" Pirot	33.918-18.039 t	0.1037	1.0	0.06	2015-2024
RSD „Jarak" Sremska Mitrovica	58.574-80.839 t	0.1037	1.0	0.06	2015-2024
RSD Pančevo	41.817-47.462 t	0.1037	1.0	0.06	2016-2024
RSD Subotica	27.978-86.916 t	0.1037	0.5	0.06	2019-2024
SD „Meteris", Vranje	23.504-19.704 t	0.1037	1.0	0.06	2015-2024
SD „Vujan", Gornji Milanovac	15.095-13.974 t	0.1037	1.0	0.06	2015-2024
RSD „Vinča", Beograd	327.980-569.968 t*	0.1085	0.5	0.06	2021-2024

Note: For all landfills, DOC_f = 0.5 and F = 0.5 were used. For the Vinča landfill, MSW_i was corrected by a factor of 0.7818 due to the existence of the WtE plant.

3.1. Comparative Overview of Annual CH₄ Emissions

Table 2 summarizes the total annual CH₄ emissions for all analyzed landfills, obtained by the Tier 1 and Tier 2 approaches. The data clearly shows a systematic overestimation of emissions when using population data and default parameters.

Table 2. Comparative overview of annual CH₄ emissions (kt CO₂e) – Tier 1 vs. Tier 2 (2021-2024)

Year	Total emissions Tier 1	Total emissions Tier 2	Relative deviation
2021	415.2	290.8	+42.8%
2022	632.4	442.7	+42.9%
2023	586.9	410.8	+42.9%
2024	542.3	379.6	+42.8%
Mean	544.2	380.9	+42.9%

3.2. Specific CH₄ Emissions and Statistical Analysis of Deviations by Landfill

Specific emissions, expressed in kg CO₂e per tonne of landfilled waste, represent a useful indicator for comparing landfill management efficiency and the impact of local parameters. By applying constant local parameters for the entire period (2021–2024), the specific emissions remained unchanged for each landfill. Table 3 presents the average values of this indicator for the observed period, along with a comparative overview of the statistical analysis of deviations between the Tier 1 and Tier 2 approaches.

Significantly lower specific emissions for the Vinča landfill (395.9 kg CO₂e/t) are a direct consequence of the existence of a WtE facility and a reduced MCF factor.

Table 3. Average Specific CH₄ Emissions and Statistical Analysis of Deviations of Tier 1 from Tier 2 Estimates by Landfill (kg CO₂e/t Waste; 2021–2024)

Landfill	Average specific emissions (kg CO ₂ e/t)	Average deviation (%)	SD within landfill (%)	95% confidence interval
RSD „Duboko" Užice	395.9	67.2	1.8	63.6-70.8
RSD „Vrbak" Lapovo	483.8	38.5	2.1	34.4-42.6
RSD Kikinda	967.7	32.4	1.5	29.4-35.4
RSD „Gigoš" Jagodina	967.7	31.8	1.7	28.4-35.2
RSD „Željkovac - D2" Leskovac	967.7	30.9	1.4	28.1-33.7
RSD „Muntina padina" Pirot	967.7	29.7	1.6	26.5-32.9
RSD „Jarak" Sremska Mitrovica	967.7	28.5	1.9	24.7-32.3
RSD Pančevo	967.7	27.8	1.3	25.2-30.4
RSD Subotica	967.7	26.4	1.5	23.4-29.4
SD „Meteris", Vranje	967.7	25.9	1.6	22.7-29.1
SD „Vujan", Gornji Milanovac	967.7	24.7	1.4	21.9-27.5
RSD „Vinča", Beograd	967.7	23.8	1.2	21.4-26.2
Weighted average	683.4	42.7	–	31.4-54.0

Note: SD within landfill represents the standard deviation of annual deviations for the given landfill (2021–2024). The standard deviation of average deviations between landfills is 11.3%. Due to the limited number of years (n = 4), confidence intervals should be interpreted as indicative measures.

Slightly higher values, though still below the average, were recorded for the Subotica landfill (483.8 kg CO₂e/t), while all other landfills show an identical value of 967.7 kg CO₂e/t due to the application of the same default parameters.

The deviation analysis shows that the Vinča landfill stands out as an extreme outlier with an average deviation of 67.2% compared to the Tier 1 calculation, followed by Subotica with 38.5%. For all landfills, the deviations were highly consistent over the four-year period, with the standard deviation within each landfill ranging from only 1.2% to 2.1%. The lowest year-to-year variability was observed at the Gornji Milanovac landfill (SD = 1.2%), while the highest was recorded for Subotica (SD = 2.1%). The weighted average deviation for all landfills is 42.7% (95% confidence interval: 31.4–54.0%), confirming a significant difference between the application of default (Tier 1) and local (Tier 2) parameters.

3.3. Graphical Presentation of Results

This section presents the graphical results of the analysis of methane (CH₄) emissions from sanitary landfills in the RoS, obtained by applying the IPCC Tier 1 and Tier 2 approaches for the period 2021–2024.

Figure 1 shows the total annual methane emissions for all 12 analyzed landfills obtained by the IPCC Tier 1 and Tier 2 approaches for the period 2021–2024. The largest absolute difference between Tier 1 and Tier 2 estimates was observed in 2022 (189.7 kt CO₂e). This peak absolute difference is primarily attributable to the highest annual waste quantities deposited across the observed landfills in that year, especially at the Vinča landfill and several other major sites. Although the relative deviation remained stable at approximately 42.9%, the absolute difference reached its maximum due to the peak waste input.

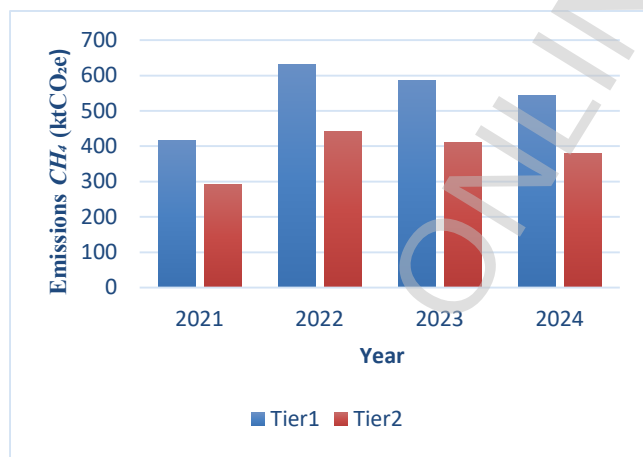


Figure 1. Annual CH₄ emissions (kt CO₂e) estimated by Tier 1 and Tier 2 IPCC FOD approaches for 12 Serbian sanitary landfills (2021–2024).

The figure 2 shows the average relative deviations for each of the 12 landfills, sorted from highest to lowest. Values are calculated as $(\text{Tier1} - \text{Tier2})/\text{Tier2} \times 100$. The Vinča landfill stands out as an extreme outlier with a deviation of 67.2%, attributed to the impact of the waste-to-energy (WtE) plant. The Subotica landfill also shows a significant deviation (38.5%) due to specific landfilling conditions (MCF = 0.5). Other landfills show more uniform,

but still significant, deviations ranging from 23.8% to 32.4%.

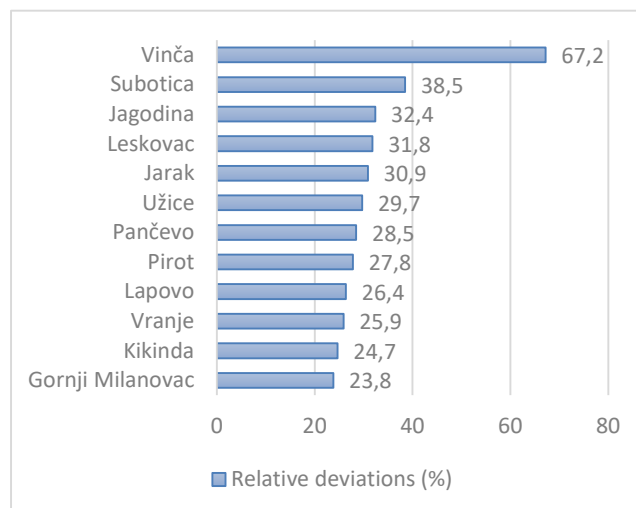


Figure 2. Relative deviations (%) of Tier 1 from Tier 2 emission estimates by landfill (average 2021–2024).

The figure 3 shows the percentage contribution of each landfill to the total methane emissions from the sanitary landfill sector in Serbia, calculated based on average values for the period 2021–2024 using the Tier 2 approach. The dominant share of the Vinča landfill (approximately 65%) is clearly highlighted, confirming its key importance for national emission inventories. Other landfills (e.g., Leskovac, Jagodina, Užice) have significantly smaller shares, indicating a high concentration of emission potential in a small number of locations.

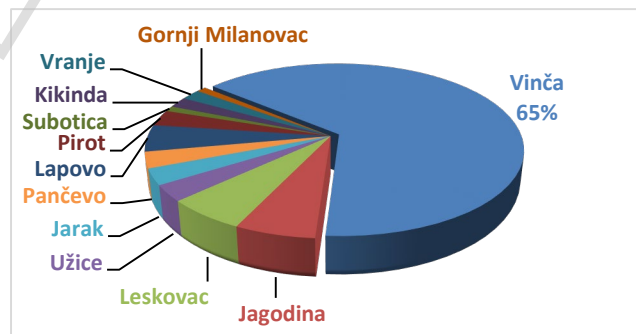


Figure 3. Share of individual landfills in total CH₄ emissions in Serbia (average 2021–2024, Tier 2 approach).

4. Discussion

4.1. Systematic Overestimation of the Tier 1 Approach

The obtained results clearly show that the Tier 1 approach, even when improved by using effective population per landfill, systematically overestimates methane emissions from sanitary landfills in Serbia. The weighted average deviation of 42.7% with a standard deviation between landfills of 11.3% indicates a significant methodological error inherent in the Tier 1 methodology, even when it is improved with local population data. It is particularly important to emphasize the dual nature of the Tier 1 error. As shown in Table S1 (Appendix), the effective population for most landfills

was estimated based on territorial or projected coverage [10]. However, the actual waste disposal system in Serbia is significantly more complex – about 13% of the population is not covered by organized waste collection, and a significant share of generated waste is still disposed of at non-sanitary or illegal dumpsites [3, 12]. This means that the MSW calculated for Tier 1 ($MSW = Pe_{ff} \times 0.95 \text{ kg/capita/day}$) is systematically higher than the quantity measured at the sanitary landfill.

However, the example of the Vinča landfill shows that Tier 1 can also underestimate the actual amount of waste. For Vinča, which serves a population of ~1.68 million inhabitants, the Tier 1 approach gives an estimate of ~583 kt of waste per year. Measured data for 2023 amount to 671,359 tonnes [13], while based on media reports the quantity for 2024 is estimated at approximately 635,000 tonnes [14]. This indicates two key conclusions:

1. For Belgrade, a higher, locally specific waste generation rate than the national average should be used;
2. At the same time, this example confirms that the assumption of complete population coverage for the capital city is more realistic than for other regions

For most other landfills, where the disposal system is more fragmented, the effect of MSW overestimation is significantly more pronounced and dominantly contributes to the overall emission deviation. This analysis further reinforces the absolute necessity of transitioning to the Tier 2 approach in official inventories.

4.2. *Applicability and Limitations of Tier 1 Methodology*

Tier 1 methodology remains a useful screening and first-approximation tool in data-scarce situations or in countries where measured waste quantities are not yet systematically available. However, as demonstrated in this study, its application using default parameters and even improved population data leads to systematic overestimation in the Serbian context. Therefore, Tier 1 should be used with caution and primarily for preliminary estimates or sensitivity analyses, while Tier 2 (or higher) is strongly recommended whenever reliable activity data exists.

4.3. *Statistical Significance and Uncertainty Analysis*

Statistical analysis confirms that the deviations between the Tier 1 and Tier 2 approaches are statistically significant for all landfills. The weighted average deviation of 42.7% with a wide confidence interval (31.4-54.0%) reflects the great variability of conditions between landfills. The low variability within each landfill (SD 1.2-2.1%) indicates the consistency of the Tier 1 error over the four-year period. Qualitative analysis of the main sources of uncertainty (MSW data, DOC, k , MCF) shows that the range of deviations is realistic and expected when default parameters are applied in specific local conditions [15].

4.4. *Accuracy of Waste Quantity Data*

The use of a single national average waste generation rate (0.95 kg/capita/day) in the Tier 1 approach does not consider significant regional, seasonal, and socio-economic

differences within Serbia [16]. This leads to an inaccurate allocation of waste quantities by landfills and is the primary cause of the basic level of deviation.

4.5. *Local Specificities of Parameters*

Default IPCC parameter values do not reflect the actual conditions in Serbia. Locally determined DOC values (0.1037-0.1085) are lower than the default value (0.15), reflecting a different morphological composition of waste (more inert, less organic) [8]. A key factor is also the reduced MCF factors for the Vinča (0.5) and Subotica (0.5) landfills, which reflect more advanced management conditions (active gas collection, specific landfilling conditions) and the direct impact of WtE technology [9].

4.6. *Effects of Waste Treatment Plants*

The waste-to-energy (WtE) plant at the Vinča landfill, operational since 2021, has a dual effect on emission reduction: it directly reduces the mass of waste deposited (factor 0.7818), and it changes the degradation conditions of the remaining waste, which is modeled with a reduced MCF factor (0.5). This effect is not covered by the Tier 1 methodology, which explains the extreme deviation of 67.2% for this landfill. This finding is in line with international experience highlighting the role of WtE plants in transforming waste management systems and reducing emissions in the Balkans [17] and is confirmed by studies analyzing the impact of different landfill management approaches on methane emissions [18].

4.7. *Limitations of Inventory Methods and the Perspective of Satellite Data Integration*

This study, like most national inventories, relies on "bottom-up" Tier 1 and Tier 2 methods. Although Tier 2 is significantly more reliable, it still has inherent limitations regarding model assumptions, parameter uncertainties, and the inability to directly verify emissions in real time [19, 20]. The future direction of research and monitoring improvement lies in the application of the Tier 3 approach, which includes direct emission measurements at the landfill (e.g., using "tracer gas dispersion" techniques) and the integration of "top-down" methods, such as satellite observations [20]. Satellite sensors, such as TROPOMI on the Sentinel-5P satellite, enable the detection and quantification of large CH_4 sources across the planet, providing an independent verification of inventory estimates [20, 21]. Recent studies indicate possible discrepancies between emission trends calculated by IPCC methods and satellite-observed atmospheric CH_4 concentrations, highlighting the need for convergence of these approaches [21]. For Serbia, developing capacities for the application of Tier 3 methods and examining the usability of satellite data for the largest landfills (such as Vinča) represents a crucial step towards a more complete and credible emission monitoring system. Comparative analyses of different landfill emission estimation methodologies further indicate the importance of selecting the appropriate approach [19, 20].

4.8. Comparison with International Studies and Contemporary Trends

The obtained results are in agreement with studies analyzing developing countries and indicate a similar range of overestimation when using Tier 1 methods [9]. The specificity of the Serbian case lies in the dominant influence of a single facility (Vinča) with integrated WtE technology, which emphasizes the need for an adapted approach in modeling. Studies analyzing waste management and energy potential in the Balkans, including the perspective of 'waste-to-energy' technologies, point to similar challenges in emission estimation and the need to transition to higher tier levels [17]. Contemporary research also shows that, although inventories (mainly based on Tier 2) in many countries have shown a decrease in emissions from the waste sector, satellite data often indicate a continuous increase in atmospheric CH₄ concentrations [21]. This apparent contradiction may indicate an insufficiently rapid reduction of emissions, significant emissions from sources not adequately covered by inventories, or the release of methane from historical deposits.

4.9. Study Limitations and Future Research Directions

This study has certain limitations: the analysis is limited to a short period (2021-2024) and only to sanitary landfills; the statistical analysis relies on a small sample. Future research should focus on:

- application of Tier 3 methods with direct measurements of landfill gas emissions (e.g., using the "tracer gas dispersion" technique) [19];
- long-term trend analysis;
- inclusion of all (including non-sanitary) landfills;
- development of adapted models for the climatic and economic conditions of the Balkans [22], in accordance with the principles of the circular economy [18].

4.10. Implications for National Climate Policy and EU Integration

The obtained results have direct implications for fulfilling Serbia's international obligations. The systematic overestimation of emissions from the waste sector by approximately 43% affects the accuracy of the national GHG inventory and can lead to incorrect planning of mitigation measures. This is especially important in the context of updating the Nationally Determined Contributions (NDCs) and preparing for alignment with EU climate regulations (Effort Sharing Regulation, Monitoring Mechanism Regulation) after accession to the European Union.

The results also indicate a high mitigation potential concentrated at a small number of locations – primarily at the Vinča landfill, which dominates with about 65% of total emissions. The expansion of technologies such as active landfill gas (LFG) collection and utilization and waste-to-energy (WtE) plants, with the possibility of Gold Standard certification (as already done at Vinča), represents the most effective path to reducing methane emissions from this sector.

5. Conclusion

The application of even an improved Tier 1 IPCC FOD approach (using effective population data and default parameters) leads to a systematic and statistically significant overestimation of methane emissions from sanitary landfills in Serbia compared to the Tier 2 approach based on measured waste quantities and locally calibrated parameters. The weighted average deviation was 42.7% (95% CI: 31.4–54.0%).

Tier 1 methodology remains appropriate only for initial screening purposes or in contexts with very limited data availability. In countries such as Serbia, where measured waste quantities from sanitary landfills are available, continued reliance on Tier 1 introduces considerable methodological uncertainty and is not recommended for final national greenhouse gas inventories.

The Vinča landfill dominates national emissions from the sanitary landfill sector with an approximate share of 65%. The largest deviations were recorded at Vinča (67.2%) and Subotica (38.5%), clearly demonstrating the strong influence of advanced waste management practices (WtE plant and reduced MCF) on emission estimates. Recommendations for improving national emission estimates:

- Continuous use of measured waste quantity data (Tier 2) as the basis for official inventories, as already applied at the Serbian Environmental Protection Agency;
- Intensifying work on determining and validating local parameters (DOC, MCF, k) for all landfills through field research;
- Development of regionalized waste generation factors to replace the single national average value;
- Explicit modeling of the effects of waste treatment plants (WtE, composting) on landfill emissions;
- Establishment of a regular landfill gas monitoring program at larger landfills to support the Tier 3 approach and model verification;
- Investigation of the possibilities for integrating satellite data ("top-down" approach) for independent verification and improvement of the accuracy of national emission inventories.

Only through the consistent application of measured data and locally adapted parameters can more realistic and reliable emission estimates be achieved, which is an indispensable basis for effective planning of climate change mitigation measures, sustainable waste management, and fulfilling Serbia's international obligations.

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ODSTUPANJA IZMEĐU TIER 1 I TIER 2 PROCENA EMISIJA METANA SA DEPONIJAMA U SRBIJI: ANALIZA PRIMENE IPCC FOD MODELA (2021–2024)

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Apstrakt

Uvod: Emisije metana (CH₄) sa deponija procenjuju se korišćenjem IPCC modela raspada prvog reda (FOD). Postoje dva nivoa: Tier 1, zasnovan na podacima o populaciji i podrazumevanim parametrima, i Tier 2, zasnovan na podacima o izmerenom otpadu i lokalno utvrđenim parametrima. Srbija deponuje preko 90% svog komunalnog otpada, ali veličina odstupanja između Tier 1 i Tier 2 još uvek nije kvantifikovana. **Metode:** Godišnje emisije CH₄ sa 12 srpskih sanitarnih deponija (2021–2024) procenjene su korišćenjem IPCC pristupa Tier 1 i Tier 2 FOD. Tier 1 je koristio podatke o efektivnoj populaciji (0,95 kg/stanovniku/dan) i podrazumevane parametre (DOC=0,15; MCF=1,0; k=0,05 god⁻¹). Tier 2 je koristio podatke o izmerenom otpadu Agencije za zaštitu životne sredine Srbije (SEPA) i lokalno utvrđene parametre (DOC=0,1037–0,1085;

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Ključne reči:
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emisije metana;
sanitarne deponije;
klimatske promene;
Srbija;

MCF=0,5–1,0; $k=0,06 \text{ god}^{-1}$). Relativna odstupanja između navedenih pristupa su izračunata i statistički analizirana. **Rezultati:** Tier 1 pristup je sistematski procenio emisije za ponderisani prosek od $42,7 \pm 11,3\%$ u poređenju sa Tier 2 pristupom. Najveće odstupanje je na deponiji Vinča (67,2%), gde postrojenje za proizvodnju energije iz otpada (WtE) i sniženi korekcioni faktor za metan (MCF=0,5) smanjuju emisije. Deponija Subotica pokazala je odstupanje od 38,5% (MCF=0,5). Deponija Vinča doprinosi približno 65% nacionalnih emisija CH₄ iz sektora sanitarnih deponija. **Zaključak:** Dalja primena Tier 1 uvodi značajno, sistematsko preceñjivanje emisija metana sa srpskih deponija. Prelazak na Tier 2 sa izmerenim podacima o otpadu i lokalno kalibrisanim parametrima je neophodan za tačne nacionalne inventare gasova sa efektom staklene bašte, efikasno planiranje mera ublažavanja i usklađivanje sa obavezama Srbije prema EU u oblasti klimatskih promena.

proizvodnja energije iz otpada;
korekcioni faktor za metan;
nacionalni inventar gasova sa
efektom staklene bašte

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