Received: 05.01.2026 Revised: 21.04.2026 Accepted: 21.05.2026 Published: 27.05.2026

**BIOLOGICAL SYSTEMS: Theory and Innovation**

ISSN 2706-8382
e-ISSN 2706-8390

**Journal homepage:** https://bioscience.com.ua/en
**Vol. 17, No. 2,** 2026, 31-47

UDC 628.4:504.06(282.243.7)

DOI: 10.31548/biologiya/2.2026.31

# Efficiency assessment of regional plastic waste collection systems in mountain and border regions: A case study of the Upper Tisza Basin

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**Abstract.** Mountain and border regions face pronounced challenges in organising efficient plastic waste collection due to complex terrain, dispersed settlement patterns and limited infrastructural capacity. These challenges are particularly critical in transboundary river basins, where mismanaged plastic waste generates cumulative downstream environmental risks. The Upper Tisza Basin, shared by Ukraine and several European Union countries, represents a high-risk area for riverine plastic transport and cross-border pollution. The aim of this study was to assess the efficiency of regional plastic waste collection systems in mountain and border conditions and to identify key factors determining system performance. The research was based on a mixed-method approach combining municipal waste statistics, geospatial accessibility analysis, field observations and qualitative assessment of municipal documentation and publicly available operational reports. System efficiency was evaluated using quantitative indicators including plastic collection rate per capita, container coverage, collection frequency and terrain-adjusted logistical performance. The results revealed substantial spatial disparities in collection efficiency. Lowland municipalities achieved plastic collection rates of 9.8-12.3 kg per inhabitant per year, whereas mountainous municipalities collected only 3.2-5.7 kg per inhabitant per year. In mountainous areas, less than 50% of residents had access to collection points within a 300 m radius, compared to over 80% in lowland settlements. Logistical inefficiency in high-altitude municipalities was more than twice as high due to poor road accessibility and elevation changes. Community-driven initiatives, including decentralised collection hubs and river clean-up programmes, increased local collection efficiency by up to 30% in underserved areas. The findings demonstrated that improving plastic waste collection in mountain and border regions requires integrated solutions combining infrastructural optimisation, terrain-sensitive logistics, institutional coordination and community engagement. The proposed assessment framework could be applied to other transboundary mountain regions to enhance environmental safety and sustainable resource use

**Keywords:** plastic waste management; spatial accessibility; border areas; riverine pollution; collection efficiency; river basin management; environmental safety

**Suggested Citation:**
Shvarts, R., & Glukh, O. (2026). Efficiency assessment of regional plastic waste collection systems in mountain and border regions: A case study of the Upper Tisza Basin. *Biological Systems: Theory and Innovation*, 17(2), 31-47. doi: 10.31548/biologiya/2.2026.31.

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## INTRODUCTION

Efficient plastic waste management is a critical component of environmental safety, particularly in mountain and border regions characterised by dispersed settlement patterns, limited infrastructural capacity and elevated transboundary ecological risks (Bhandari *et al.*, 2021). In such territories, insufficient waste collection systems contribute not only to local environmental degradation but also to the accumulation and downstream transport of plastic waste through shared river basins. This problem is especially significant in the Upper Tisza Basin, where complex terrain, hydrological connectivity and uneven municipal service provision increased the likelihood of riverine plastic leakage beyond administrative and national boundaries. In the Ukrainian upstream section of the basin, within the Zakarpattia region, significant disparities in accessibility, settlement density, and collection infrastructure have led to uneven conditions for separate plastic waste collection. As a result, assessing the efficiency of the system is crucial for understanding environmental safety at the basin level, as noted by C.C. Chen (2010). Recent comprehensive evaluations of the Carpathian watercourses, as identified by M. Liro *et al*. (2023), have highlighted this macroregion's high vulnerability to mismanaged plastic waste, with notable hotspots in Ukraine, Romania, and Hungary.

Recent scientific literature increasingly addressed the challenges of plastic waste management in geographically constrained and environmentally sensitive regions. As highlighted by F.-C. Mihai *et al*. (2022), indicates that rural and mountain communities face ongoing infrastructural deficiencies, limited service coverage, and restricted capacity for implementing circular economy practices, all of which heighten the risk of unmanaged plastic waste accumulation outside urban areas. Meanwhile, recent evaluations of Carpathian watercourses, conducted by M. Liro *et al*. (2023), have confirmed the macroregion's significant vulnerability to mismanaged plastic waste and the formation of hotspots along river corridors, including within Ukraine. These findings supported the relevance of evaluating plastic waste collection efficiency in the Ukrainian section of the Upper Tisza Basin as a mountain-border territory exposed to both local service deficits and downstream environmental risks. The study by U. Leknoi *et al*. (2024) explores sustainable community building through successful waste management initiatives, providing valuable insights into effective practices that can be applied in rural and mountain communities to mitigate plastic waste accumulation. On the other hand, the study by V. Nava *et al*. (2024) investigates how plastic pollution impacts ecosystem processes, including community structure and functional traits in large rivers. This study is highly relevant, as it underscores the broader ecological consequences of mismanaged plastic waste, particularly along river corridors. Previous studies on the Tisza River by T. Kiss *et al*. (2021) have shown that local sources in tributaries play a significant role in the spatial distribution of plastic pollution, highlighting the complexity of transboundary sediment and waste transport. Studies focusing on mountain waste management in the Carpathian region have shown that infrastructure gaps and policy inconsistencies at the municipal level lead to uneven service provision and higher risks of illegal dumping in remote settlements. These findings indicate that mountainous terrain significantly increases logistical complexity and requires differentiated management approaches rather than uniform national strategies.

Despite the growing body of research on waste management, existing studies have mainly focused on urban systems or national-level frameworks, while integrated assessments of plastic waste collection in transboundary mountain regions remain limited. In particular, insufficient attention has been paid to municipal-level plastic collection efficiency in upstream territories where geographical constraints, infrastructural accessibility, institutional capacity and community participation directly influence cross-border riverine pollution dynamics. This research gap highlights the need for a region-specific analytical framework that combines spatial accessibility analysis, quantitative performance indicators and institutional evaluation to better understand how collection inefficiencies translate into environmental safety risks at the basin scale. The present study addressed this gap by conducting a systematic efficiency assessment of plastic waste collection systems within the Ukrainian section of the Upper Tisza Basin. Particular attention was

devoted to the interaction between infrastructural distribution, logistical constraints, institutional capacity and community engagement in shaping municipal-level performance. The objective of this research was to determine how geographical and governance-related factors influenced the efficiency of plastic waste collection in a transboundary mountain basin and to identify priority directions for improving environmental safety through enhanced waste management performance.

## MATERIALS AND METHODS

**Study area.** The study was conducted within the Ukrainian section of the Upper Tisza Basin, located in Zakarpattia region in western Ukraine. The analysed territory included municipalities situated within the hydrological boundaries of the Upper Tisza River and its tributaries upstream of the Ukrainian-Hungarian border. Geographically, the study area extended between approximately 47°53′-48°45′ N latitude and 22°08′-24°30′ E longitude. The assessment covered municipalities belonging to Uzhhorod, Mukachevo, Khust, Rakhiv and Tyachiv districts, encompassing both lowland settlements in the western part of the region and mountainous communities located in the Carpathian highlands. Particular attention was devoted to municipalities situated along the Tisza River and its tributaries, including the Uzh, Latorytsia, Rika and Tereblia rivers. These river systems functioned as primary hydrological pathways facilitating the transport of mismanaged plastic waste during flood events.

The study area is characterised by pronounced altitudinal variation ranging from approximately 100 metres above sea level in lowland territories to over 2,000 metres in mountainous zones. Settlement patterns differed substantially between districts: lowland municipalities demonstrated higher population density and more developed road infrastructure, whereas mountainous communities were characterised by dispersed settlements, limited transport accessibility and seasonal road constraints. Seasonal factors were considered in the analysis. Tourist flows in mountain municipalities increased during summer and winter recreational periods, leading to temporary growth in municipal solid waste generation. Additionally, spring flood events significantly influenced plastic waste mobilisation and riverine transport. These seasonal dynamics were incorporated into the interpretation of collection efficiency and leakage risks.

**Research design and data collection.** A mixed-method research design was applied to assess the efficiency of plastic waste collection systems in the Upper Tisza Basin. The methodological framework combined quantitative analysis of municipal waste indicators with spatial modelling and qualitative institutional assessment. The integration of multiple analytical approaches ensured methodological triangulation and enhanced the reliability of findings. The research design incorporated: statistical analysis of municipal waste management data; geospatial accessibility assessment of collection infrastructure; field observations of collection points and informal dumping sites; document-based qualitative analysis of institutional and operational practices.

Data were collected for the period 2022-2024 from official statistical and administrative sources. Demographic indicators for the study area were derived from the State Statistics Service of Ukraine & the Main Department of Statistics in Zakarpattia Region (2022), including district-level population estimates as of 1 January 2022. Regional contextual data on waste-management conditions, disposal infrastructure and environmental pressures were compiled from the Environmental Passport of Zakarpattia Region for 2022 (2023) and Environmental Passport of Zakarpattia Region for 2023 (2024) and from the Regional Waste Management Plan of Zakarpattia Region to 2030 (Zakarpattia Regional State Administration, 2021). Municipality-level information on collection infrastructure, service frequency and local organisational arrangements was compiled from publicly available reports and official webpages of the selected municipalities and municipal service providers within the study area.

Geospatial data were derived from open-access satellite imagery and digital spatial datasets. Sentinel-2 imagery was accessed through the Copernicus Data Space Ecosystem (n.d.) for land-use verification and visual interpretation. Elevation data were obtained from the Shuttle Radar Topography Mission (SRTM) digital elevation model distributed through the USGS EarthExplorer (n.d.) platform. Road-network and settlement-related spatial data were derived from OpenStreetMap (n.d.) datasets. Spatial processing and analysisCwere performed

in QGIS. Spatial analysis was conducted using QGIS software (version 3.x). GIS-based modelling enabled the mapping of official plastic collection points in relation to settlement distribution, road accessibility and elevation gradients. Buffer analysis was applied to estimate service coverage within a 300-metre walking radius. Terrain constraints were assessed through slope analysis derived from the DEM (Digital Elevation Models) dataset.

Field observations were conducted during 2023 in selected lowland and mountainous municipalities of Zakarpattia region, including Uzhhorod urban territorial community, Mukachevo urban territorial community, Rakhiv urban territorial community, Tyachiv urban territorial community and Mizhhiria settlement territorial community. On-site inspections focused on the physical condition of collection points, evidence of overflow, proximity to watercourses and signs of informal dumping along riverbanks and forest roads. Qualitative assessment was based on document analysis of publicly available municipal reports, official webpages of local authorities and communal service providers, and field observation records from the study area. No interviews, questionnaires or other forms of direct human-subject data collection were conducted in this study. As the analysis relied exclusively on aggregated statistical data and publicly accessible institutional information, no personal data were processed and no additional ethical approval was required.

Community-engagement data were compiled from publicly available materials of civic and project-based waste initiatives active in Transcarpathia during 2022-2024, particularly the Plastic Cup/PET Kupa initiative and the CALL-Action programme (Plastic Cup, 2023; Interreg Danube Region, 2024). Analysed information included publicly reported amounts of collected or processed waste, references to Ecobus and other collection activities, territorial coverage of actions, and the geographic focus of community-based interventions in Uzhhorod, Berehove and other Tisza-adjacent settlements. These materials included official project webpages, public reports of clean-up organisers and online summaries of cross-border river-cleaning actions published during 2022-2024.

Geospatial assessment constituted a core component of the methodological framework. All officially reported plastic waste collection points were mapped within a GIS environment and analysed in relation to settlement distribution, road networks and elevation gradients. Spatial modelling was conducted in QGIS using vector-based municipal boundaries and raster-based elevation data. Service accessibility was evaluated using buffer analysis with a 300-metre walking radius around each collection point. This threshold was applied in accordance with commonly used accessibility standards in municipal waste management studies. Catchment areas were overlaid with population distribution data to estimate the proportion of residents with direct access to plastic collection infrastructure. Terrain-related constraints were quantified through slope analysis derived from the SRTM digital elevation model. Road accessibility was evaluated based on distance to paved roads extracted from OpenStreetMap datasets. These spatial indicators were later incorporated into the logistical accessibility index.

**Efficiency indicators and index calculation.** To ensure comparability across municipalities with differing geographical and socio-economic characteristics, quantitative indicators were normalised using min-max scaling. Normalisation was performed according to equation (1):

$$X_{norm,i} = \frac{X_i - X_{min}}{X_{max} - X_{min}}, \quad (1)$$

where $X_i$ represented the observed value of the indicator for municipality $i$, and $X_{min}$ and $X_{max}$ denoted the minimum and maximum values across the study area. A Logistical Accessibility Index (LAI) was calculated to reflect terrain-related operational constraints:

$$LAI_i = \sum_{j=1}^{n} w_j \cdot X_{norm,j}, \quad (2)$$

where $X_{norm,j}$ represented normalised terrain-related variables, including elevation gradient and road accessibility. Equal weighting coefficients ($wj$) were applied due to the absence of prior empirical evidence supporting differential weighting. A composite Plastic Waste Collection Efficiency Index (PWCE) was derived by integrating the primary performance indicators:

$$\mathrm{PWCE}_i = \frac{CR_i + CC_i + CF_i + \mathrm{LAI}_i}{4}, \quad (3)$$

where *CR* represented the normalised plastic collection rate per capita; *CC* represented container

coverage; *CF* denoted collection frequency; LAI represented logistical accessibility. All four dimensions were weighted equally to avoid introducing subjective bias. The resulting composite index ranged from 0 to 1, where higher values indicated greater collection efficiency. These indices were subsequently used in the Results section to compare performance disparities between lowland and mountainous municipalities.

In addition to municipal efficiency assessment, the integrated analytical framework was used to formulate a conceptual model for evaluating plastic waste collection efficiency in mountain-border regions. The model was derived from the combined interpretation of geospatial accessibility indicators, operational performance metrics, institutional constraints and community-participation factors identified during the study. Equal weighting was retained at the indicator aggregation stage, while interdependencies between dimensions were interpreted qualitatively in the Discussion section, including the influence of seasonal variability (tourism peaks and flood periods) on system performance.

**Qualitative analysis.** Qualitative analysis complemented the quantitative and spatial assessment by providing contextual interpretation of institutional and operational factors influencing plastic waste collection efficiency. Analytical review of municipal reports, publicly available operational documentation and field observation notes was conducted using thematic categorisation. The qualitative evaluation focused on four principal dimensions: institutional coordination between municipalities and waste operators; financial and logistical constraints affecting service provision; public awareness and participation patterns; interactions between formal waste management systems and community-based initiatives. Thematic coding allowed the identification of recurring structural barriers, including fragmented governance arrangements, limited municipal budgets and infrastructure deficits in mountainous territories. Qualitative findings were used to interpret disparities revealed by quantitative efficiency indicators.

## RESULTS AND DISCUSSION

### Infrastructure distribution and accessibility

The analysis revealed pronounced disparities in the distribution and accessibility of plastic waste collection infrastructure across municipalities of the Ukrainian section of the Upper Tisza Basin. Higher levels of infrastructure coverage were identified in lowland municipalities of Uzhhorod and Mukachevo districts, where denser settlement patterns and better road connectivity supported more frequent servicing and a greater number of collection points. In contrast, mountainous municipalities of Rakhiv, Tyachiv and Khust districts demonstrated substantially lower infrastructure density, especially in remote settlements located along upper tributaries and valley-based settlement clusters (State Statistics Service of Ukraine & the Main Department of Statistics in Zakarpattia Region, 2022).

GIS-based accessibility assessment (utilising the buffer approach alongside indicator normalisation as described in equation (1) and subsequent index integration) showed that lowland municipalities generally had a substantially larger share of residents living within a 300-metre walking distance of official plastic collection points. In mountainous communities, this proportion was markedly lower due to dispersed settlement patterns, steep slopes and limited road access. Spatial mismatches between container placement and residential distribution were observed most clearly in peripheral villages and hamlets with fragmented street networks (Kwikima & Ngole, 2025). Terrain-related constraints significantly affected operational feasibility. Slope conditions, distance to paved roads and local road quality reduced the practicality of installing and regularly servicing additional collection points in high-altitude settlements. These constraints were reflected in lower values of the logistical accessibility component (LAI, equation (2)), which was later incorporated into the composite plastic waste collection efficiency index (PWCE, equation (3)).

From an environmental safety perspective, uneven infrastructure accessibility increased the risk of unmanaged plastic accumulation near households, roadside areas and watercourses. In municipalities with limited collection coverage, the absence of convenient disposal options created conditions for informal dumping and litter leakage into tributaries of the Tisza River. Such infrastructure deficits therefore represented not only a service performance problem but also a direct factor contributing to riverine plastic pollution

and transboundary environmental risk formation (Environmental Passport of Zakarpattia Region for 2022, 2023). Seasonal factors further intensified these disparities. During periods of heavy rainfall and spring flood events, access to remote collection points became less reliable in mountainous areas, which increased the likelihood of delayed collection and local overflow. In tourist-active mountain municipalities, temporary increases in waste generation placed additional pressure on already limited infrastructure, particularly near recreation zones and river-adjacent settlements (Environmental Passport of Zakarpattia Region for 2023, 2024).

Overall, the spatial assessment demonstrated that infrastructure distribution and accessibility constituted foundational determinants of municipal plastic waste collection performance in the Upper Tisza Basin. The observed territorial disparities also indicated that improvements in environmental safety at the basin scale depended on targeted infrastructure planning in underserved upstream mountain communities rather than on uniform expansion measures across all municipalities. Furthermore, the findings suggested that a more localised, context-specific approach to infrastructure development would be crucial for addressing the unique challenges faced by these communities in managing plastic waste effectively.

**Collection performance and quantitative indicators**

Significant inter-municipal differences were identified in the quantitative indicators of plastic waste collection performance across the Ukrainian section of the Upper Tisza Basin. The comparative assessment showed that municipalities located in lowland districts demonstrated consistently higher collection efficiency than mountainous communities. This pattern reflected the combined influence of infrastructure density, service frequency and terrain-related logistical accessibility. The quantitative indicators presented in Table 1 were calculated using the normalisation and composite-index procedures described in equations (1-3). In particular, equation (1) was applied for min-max normalisation of municipal indicators, equation (2) was used to derive the logistical accessibility index, and equation (3) was used to calculate the composite plastic waste collection efficiency index.

**Table 1.** Comparative indicators of plastic waste collection efficiency in lowland and mountainous municipalities of the Ukrainian section of the Upper Tisza Basin

| Indicator | Lowland municipalities | Mountainous municipalities |
|---|---|---|
| Plastic collection rate (kg/inhabitant/year) | 9.8-12.3 | 3.2-5.7 |
| Container coverage (units per 1,000 inhabitants) | 12-15 | 4-6 |
| Population with access to collection points within 300 m (%) | 80-85 | 35-50 |
| Collection frequency (rounds per month) | 6-8 | 2-3 |
| LAI | 0.68-0.81 | 0.29-0.44 |
| Composite PWCE | 0.71-0.83 | 0.34-0.48 |

**Note:** indicator values are presented as ranges reflecting inter-municipal variability within each group. LAI was calculated using equation (2); PWCE values were calculated using equation (3) after indicator normalisation according to equation (1). "Lowland municipalities" refer to municipalities predominantly located in Uzhhorod and Mukachevo districts; "mountainous municipalities" refer to municipalities predominantly located in Rakhiv, Tyachiv and Khust districts
**Source:** developed by the authors based on State Statistics Service of Ukraine & the Main Department of Statistics in Zakarpattia Region (2022)

Table 1 demonstrates that the strongest disparities between municipality groups were observed in container coverage, service accessibility within a 300-metre radius and collection frequency. These parameters directly influenced both the plastic collection rate and the composite PWCE values, indicating that municipal performance depended on the combined effect of infrastructure availability and operational feasibility. From an environmental safety perspective, the lower indicator values recorded in mountainous municipalities indicated a higher probability of unmanaged plastic accumulation and subsequent riverine leakage into the Tisza tributary network. Lowland munic-

ipalities achieved higher plastic collection rates per inhabitant and better container coverage, which corresponded to a larger population share with direct access to collection points. In contrast, mountainous municipalities demonstrated lower collection rates and lower service coverage, indicating structural limitations in infrastructure provision and collection logistics. The identified disparities confirmed that insufficient accessibility and lower collection frequency remained key constraints on the performance of plastic waste collection systems in mountainous territories.

Operational frequency also differed substantially between municipality groups. More frequent collection rounds in lowland areas reduced the probability of container overflow and secondary littering near collection points, while lower collection frequency in mountainous communities increased the risk of local plastic accumulation. This difference had direct environmental implications, as delayed collection in settlements located near tributaries increased the likelihood of plastic leakage into river systems during heavy rainfall and flood-related runoff events. The logistical accessibility index (LAI) and the composite PWCE values demonstrated the cumulative effect of terrain constraints on municipal system performance. Lower LAI values in mountainous municipalities reflected poorer road access and more difficult topographic conditions, which reduced service efficiency even where collection points were formally present. Therefore, the results indicated that infrastructure expansion alone would not be sufficient without simultaneous improvements in route planning, seasonal service adaptation and local collection logistics.

**Riverine plastic leakage**

Field observations conducted in 2023 in Uzhhorod urban territorial community, Mukachevo urban territorial community, Rakhiv urban territorial community, Tyachiv urban territorial community and Mizhhiria settlement territorial community, together with publicly available materials from the Plastic Cup / PET Kupa initiative and the CALL-Action programme, indicated that riverine plastic leakage remained a significant environmental safety problem in the Ukrainian section of the Upper Tisza Basin (Plastic Cup, 2023; Interreg Danube Region, 2024). Plastic waste accumulation was observed along riverbanks, floodplain margins and riparian vegetation, particularly near settlements with limited collection infrastructure and lower service frequency. The most frequently observed fractions included PET bottles, packaging film and disposable food packaging. This pattern was consistent with broader scientific evidence showing that rivers and riparian zones function both as transport pathways and as retention zones for macroplastic accumulation (Gallitelli & Scalici, 2022).

The spatial pattern of leakage hotspots in the observed municipalities corresponded to settlement clusters characterised by insufficient infrastructure accessibility and irregular collection schedules. In such locations, unmanaged plastic waste accumulation near households, roadsides and local drainage pathways increased the probability of transport into tributaries during precipitation events. This pattern strengthened the link between municipal waste collection efficiency and downstream environmental risk formation in the Tisza basin. Seasonal dynamics played an important role in leakage intensity. During spring floods and periods of heavy rainfall, accumulated plastic waste from floodplains and near-channel areas was mobilised and transported downstream. In mountain municipalities with seasonal tourism, temporary increases in waste generation during recreation periods placed additional pressure on local collection systems and contributed to higher plastic accumulation near river-adjacent settlements and informal recreation zones. Publicly available reports and cross-border initiative materials also confirmed the relevance of the Upper Tisza and wider Tisza basin as a hotspot of riverine plastic transport. Peer-reviewed evaluations of citizen science campaigns, such as the PET Kupa initiative, combined with remote sensing, have documented the repeated large-scale removal of macroplastic waste from the Tisza system, emphasising that upstream source-management deficits directly drive downstream pollution dynamics (Di *et al*., 2025). International academic reviews on riverine litter further highlighted the practical role of coordinated clean-up actions and prevention-oriented basin management for reducing transboundary plastic pollution.

Community clean-up initiatives operating in the region provided additional indirect evidence of persistent leakage pressure by regularly reporting

collected volumes, recurring hotspot locations and repeated accumulation after flood events. These observations indicated that clean-up actions, while environmentally beneficial, did not substitute for systematic improvements in municipal collection coverage and service accessibility in upstream settlements. From an environmental protection perspective, riverine plastic leakage in the Upper Tisza Basin represented a cumulative risk mechanism linking local infrastructure deficits with downstream ecological impacts. The findings indicated that targeted improvements in upstream plastic collection systems could reduce plastic transfer into transboundary river channels and strengthen basin-scale environmental safety.

**Institutional and socio-economic factors**

Institutional and socio-economic conditions substantially influenced the performance of plastic waste collection systems across municipalities of the Ukrainian section of the Upper Tisza Basin. Analysis of municipal documentation, official webpages of local authorities and communal service providers, regional planning materials, and field observation records indicated that mountainous municipalities faced more persistent organisational and service-related constraints than lowland municipalities (Zakarpattia Regional State Administration, 2021; Environmental Passport of Zakarpattia Region for 2022, 2023). In practice, these constraints were reflected in lower service frequency, weaker infrastructure coverage and greater operational instability in remote settlements. Institutional fragmentation further complicated service delivery in geographically dispersed territories. In the observed municipalities, waste collection responsibilities were divided between local authorities, communal enterprises and contracted operators, which reduced consistency in route planning, servicing schedules and monitoring practices. These coordination difficulties were more visible in mountainous municipalities, where long travel distances, road limitations and dispersed settlement structure increased the dependence of service efficiency on well-coordinated operational arrangements. This interpretation was consistent with broader evidence showing that fragmented governance reduces the effectiveness of municipal waste services in territorially complex settings.

Socio-economic differences between lowland and mountainous municipalities also affected the practical functioning of separate collection systems. Infrastructural accessibility remained the dominant determinant of use; however, field observations and document analysis suggested that the visibility of collection points, regularity of servicing and presence of local environmental outreach activities also influenced the practical use of separate collection infrastructure. In municipalities where collection points were sparse or collection rounds were irregular, lower practical utilisation of designated plastic containers was observed, together with more frequent mixed disposal near collection sites (Environmental Passport of Zakarpattia Region for 2023, 2024). The community-participation dimension considered in the qualitative interpretation of results. It was interpreted as a contextual characteristic derived from observable local activity patterns, publicly documented outreach practices and the documented presence of community-driven environmental initiatives within the municipality groups. This approach reduced the risk of overstating behavioural explanations where infrastructural and logistical constraints remained the primary limiting factors.

From an environmental safety perspective, institutional and socio-economic limitations increased the probability that infrastructure deficits would translate into unmanaged plastic accumulation in residential and river-adjacent areas. These factors therefore amplified the environmental consequences of already existing geographical and logistical constraints, especially in upstream mountain municipalities. As a result, the inability to address these limitations could lead to the worsening of plastic pollution, further endangering local ecosystems and complicating future environmental management efforts.

**Role of community-driven initiatives**

Community-driven initiatives demonstrated a significant complementary role in improving plastic waste collection performance in underserved municipalities of the Ukrainian section of the Upper Tisza Basin. The qualitative and comparative assessment indicated that volunteer clean-up campaigns, local decentralised collection practices and cross-border environmental

actions partially compensated for infrastructural and logistical limitations of formal municipal waste services, especially in mountain settlements with difficult access. Concrete examples included activities associated with the Plastic Cup / PET Kupa network and the CALL-Action programme operating in Transcarpathia and the wider Tisza basin (Plastic Cup, 2023; Interreg Danube Region, 2024). Publicly available project materials documented selective waste collection support, Ecobus-related activities, repeated clean-up actions and broader community engagement measures in Uzhhorod, Berehove and other Tisza-connected settlements. These initiatives contributed not only to the direct removal of accumulated waste from river-adjacent areas, but also to the visibility of the plastic-waste problem at community level.

The comparative analysis also indicated that municipality groups where community-led activities were present tended to demonstrate higher average composite efficiency values (PWCE) than municipality groups relying exclusively on formal waste collection services. This pattern was particularly evident in mountainous municipalities, where decentralised local actions improved interim collection, sorting and transfer of plastic waste in areas with irregular municipal servicing. From an environmental management perspective, the role of community initiatives should be interpreted as complementary rather than substitutive. Their practical contribution was greatest where formal infrastructure coverage and service regularity remained insufficient. The quantitative comparison of municipality groups with and without community-driven initiatives is presented in Table 2.

**Table 2.** Influence of community-driven initiatives on plastic waste collection efficiency in selected municipality groups of the Ukrainian section of the Upper Tisza Basin

| Municipality type | Presence of community initiatives | PWCE (average) | Increase in collection efficiency (%) |
|---|---|---|---|
| Lowland | No | 0.72 | – |
| Lowland | Yes | 0.81 | +12 |
| Mountainous | No | 0.36 | – |
| Mountainous | Yes | 0.47 | +30 |

**Note:** PWCE – composite Plastic Waste Collection Efficiency Index calculated according to equation (3) after normalisation of component indicators under equation (1); "Presence of community initiatives" indicates the documented presence of volunteer clean-up campaigns, decentralised collection hubs or local environmental outreach activities within the municipality group; "Increase in collection efficiency (%)" shows the relative difference in average PWCE values between municipality groups with and without such initiatives; "–" – no data available
**Source:** developed by the authors

Table 2 indicated that the association between community-driven initiatives and improved collection efficiency was stronger in mountainous municipalities than in lowland municipalities. This result suggested that local volunteer actions and decentralised collection practices played a compensatory role where formal infrastructure coverage and service frequency remained limited. At the same time, the table also showed that community initiatives complemented rather than replaced formal municipal systems, as the highest efficiency values were observed where community engagement operated alongside more stable collection infrastructure and regular servicing. Overall, the findings confirmed that community-driven initiatives constituted an important adaptive mechanism for improving plastic waste management performance in mountain-border regions. Their greatest practical value was observed in settlements with infrastructural deficits, where local actions reduced leakage risks and supported interim recovery of plastic waste. From an environmental safety perspective, integration of community initiatives into municipal planning represented a feasible and cost-effective direction for reducing riverine plastic pollution in upstream areas of the Upper Tisza Basin.

### Influence of geographical and infrastructural constraints on operational efficiency

The results of the present study are consistent with recent evidence showing that waste collection

performance in mountain and low-density territories depends not only on the formal availability of infrastructure, but also on the practical relationship between settlement structure, collection mode and route feasibility. A.P.D. Baltrocchi *et al*. (2024), comparing mixed and full door-to-door separate collection systems in two mountainous Italian valleys, demonstrated that collection performance in mountainous areas was strongly affected by territorial configuration and service design. Their results showed that the full door-to-door system achieved better separate-collection performance than the mixed system, indicating that the effectiveness of waste collection in mountain territories cannot be assessed by infrastructure presence alone. This was consistent with the findings of the present study, where municipalities with formally existing collection points still demonstrated lower collection efficiency when accessibility, road conditions and settlement dispersion limited practical service use.

A broader mountainous-region perspective was provided by K. Zhou *et al*. (2024), who developed an integrated framework for assessing environmental risks of domestic waste management systems in mountainous regions. Their study emphasised the combined role of scattered settlements, ecological fragility, limited traffic accessibility and low disposal capacity in generating elevated environmental risks. The Upper Tisza Basin findings were similar in that mountainous municipalities combined weaker infrastructure coverage with more difficult access and greater operational instability. However, the present study extended this perspective by linking these territorial disadvantages specifically to plastic collection efficiency and to riverine leakage risk in an upstream transboundary basin. The geospatial dimension of the present analysis also corresponded to recent GIS-based optimisation research. M.M. Kwikima & F. Ngole (2025), in a case study from Sumbawanga municipality, showed that GIS-based optimisation of collection points and routes substantially improved service coverage and reduced fuel use and driver hours. This supported the methodological relevance of spatial accessibility analysis in the present study, where QGIS-based assessment helped reveal that the weakest-performing municipalities were not simply those with fewer containers, but those where container location, dispersed settlement structure and route difficulty interacted to reduce actual service effectiveness.

Overall, the comparison indicated that geographical and infrastructural constraints should be interpreted as structural determinants of waste collection efficiency, but their practical effects depended on service design, routing logic and territorial configuration. In this respect, the Upper Tisza Basin case contributed a more environmentally specific interpretation by demonstrating that in upstream mountain municipalities these operational inefficiencies also increased the probability of plastic leakage into river corridors with transboundary consequences. Moreover, the study highlighted the need for region-specific solutions that consider the unique challenges of these areas, ensuring more effective waste management strategies to mitigate the cross-border environmental risks.

**Riverine leakage and seasonal dynamics**

The interpretation of riverine leakage in the present study was consistent with region-specific evidence showing that mountain river systems of the Carpathians are highly exposed to mismanaged plastic waste inputs. M. Liro *et al*. (2023), using high-resolution river-network and mismanaged plastic waste databases for the Carpathian Ecoregion, identified extensive plastic-waste hotspots along Carpathian watercourses, including substantial hotspot lengths in Ukraine. This comparison was important for the Upper Tisza Basin because it confirmed that the observed leakage risk was not an isolated local anomaly, but part of a broader mountain-river pattern in which river corridors function as receivers and conveyors of mismanaged plastic waste.

A more direct transboundary comparison was provided by T. Kiss *et al*. (2021), who analysed microplastic deposition along the Tisza River and its tributaries and found that tributaries transported large amounts of microplastics into the main river, while the most upstream sections showed particularly high contamination associated with lower levels of wastewater management. The present study was consistent with this upstream-downstream logic, but extended it from sediment contamination to municipal collection performance by showing that infrastructural and service deficiencies at municipality level could be interpreted as practical drivers of leakage risk into tributaries

and the main Tisza channel. The seasonal dimension identified in the present study was also supported by recent flood-focused river-plastic research. T.H.M. van Emmerik *et al*. (2023) demonstrated that extreme floods strongly amplify plastic mobilisation, transport and retention in river systems, with a substantial share of annual plastic transport occurring during a short flood period. This comparison supported the interpretation that spring floods and high-rainfall episodes in the Upper Tisza Basin were not merely background hydrological conditions, but critical temporal windows during which previously accumulated plastic waste was redistributed from riverbanks, floodplains and near-channel accumulation zones into the active river network. This interpretation is further supported by a recent review E.K. Owowenu *et al*. (2023) showing that precipitation, run-off, flow velocity, channel morphology and riparian trapping strongly influence plastic transport dynamics in riverine systems.

The tourism-related seasonal pressure identified in mountain municipalities also corresponded to broader rural plastic-pollution evidence. F.-C. Mihai *et al*. (2022) argued that rural communities should be understood both as contributors to plastic leakage and as receivers of pollution pressures, and specifically noted the relevance of tourism-related plastic pollution in rural environments. In the Upper Tisza Basin, this perspective helped explain why temporary increases in visitor numbers in river-adjacent recreation areas could intensify plastic accumulation even where permanent population density remained low. Overall, the comparison with recent literature indicated that riverine leakage in the Upper Tisza Basin should be interpreted as a dynamic interaction between municipal service limitations, riparian retention processes and seasonal hydrological remobilisation. In this respect, the present study contributed a municipality-level explanation of why upstream collection inefficiencies in a mountain-border basin could generate cumulative downstream environmental risks with transboundary relevance.

**Institutional limitations and governance challenges**

The institutional barriers identified in the present study were consistent with broader evidence showing that fragmented governance structures reduced the effectiveness of municipal waste management systems in rural and border regions (Popa, 2022). A similar pattern was observed in the Upper Tisza Basin, where differences in municipal capacity, operator arrangements and local service planning contributed to uneven collection performance. Comparable conclusions have been reported in previous studies of municipalities, which showed that policy inconsistencies and infrastructure deficits, combined with limited local institutional capacity, contributed to territorial inequality in waste service provision (Popa, 2022; Zhang *et al*., 2023). The present study supported this interpretation by demonstrating that municipalities with constrained budgets and organisational fragmentation faced greater difficulty in maintaining regular collection schedules and extending services to remote settlements. The governance-related interpretation of the present findings was consistent with broader research on rural waste service efficiency, where operational inefficiencies were associated not only with accessibility constraints but also with planning and service management limitations. In the Upper Tisza Basin, geographical barriers remained highly influential; however, the results indicated that institutional coordination affected the extent to which these barriers translated into persistent service instability.

The socio-economic dimension discussed in the present study also corresponded to broader evidence indicating that household participation in separate collection depended on the interaction between service accessibility, local outreach practices and the predictability of municipal collection systems (Zhang *et al*., 2023). In this respect, the findings supported the view that behavioural engagement was stronger where local initiatives and visible collection practices encouraged routine participation. At the same time, the present study differed from purely behavioural interpretations by showing that socio-economic and awareness-related factors should be interpreted within the constraints imposed by infrastructure and logistics. In the Upper Tisza Basin, low participation in mountainous municipalities could not be adequately explained without considering sparse collection-point distribution and irregular servicing. This comparison suggested that governance reforms and awareness activities were most effective when implemented alongside improvements

in practical service accessibility. Overall, institutional fragmentation and unequal municipal capacity represented major constraints on waste collection efficiency in mountain-border regions. The Upper Tisza Basin case added further evidence that these governance limitations had direct environmental safety implications when they interacted with upstream riverine leakage pathways in a transboundary basin system.

**Effectiveness of community-driven initiatives**

The results of the present study are consistent with recent evidence showing that community-based waste initiatives can improve local waste-management performance when they are embedded in stable local organisational structures. U. Leknoi *et al*. (2024), analysing a community-led waste-management initiative in a low-income area near Bangkok, demonstrated that successful local action depended on broad participation, practical leadership and context-specific organisational arrangements. Their study showed that waste separation and community-led management could reduce local pollution pressures even under conditions of limited budgets and technological constraints. This was comparable to the Upper Tisza Basin findings, where community-driven initiatives partially compensated for infrastructural and logistical deficits in underserved municipalities.

A broader governance-oriented comparison was provided by S. Wang *et al*. (2025), who analysed 26 community waste-management experiments in China and identified three main pathways to success: committed participants supported by dedicated communities, committed participants backed by local government, and strong grassroots leadership combined with responsible public support. This comparison was particularly relevant to the present study because it confirmed that community initiatives were most effective when they operated together with municipal structures rather than independently of them. In the Upper Tisza Basin, the same pattern was observed: municipalities with documented community engagement achieved better practical waste-recovery performance, but the strongest results were associated with combinations of civic action, regular service provision and more stable infrastructure coverage. Compared with these studies, the Upper Tisza Basin case added a specific environmental-safety dimension. Here, community-driven initiatives are relevant not only because they improved local collection and sorting practices, but also because they reduce plastic accumulation in river-adjacent and upstream settlements where unmanaged waste could later be mobilised into tributaries of the Tisza. In this respect, the present study extends previous evidence by showing that in mountain-border river basins community action may have both a service-supporting function and a preventive role in reducing transboundary leakage risks.

**Environmental safety implications and management relevance**

The environmental-safety implications identified in the present study are consistent with recent evidence showing that plastic pollution in rivers affects not only water quality and biodiversity, but also broader ecosystem processes. V. Nava *et al*. (2024), analysing plastic pollution in large rivers, demonstrated that biofouled plastics altered community structure, metabolic functioning and oxygen conditions, with potentially profound ecosystem-level consequences. This comparison was relevant to the Upper Tisza Basin because it supported the interpretation that municipal plastic-collection deficiencies in upstream areas should be viewed not merely as a service-performance problem, but as a source of wider ecological disturbance in river systems.

The present findings are also consistent with emerging process-based evidence that plastic pollution can modify the physical functioning of rivers. C.E. Russell *et al*. (2023) showed that plastic in riverbeds was not a passive pollutant, but could alter sediment transport processes, bedform dynamics and the spatial distribution of plastic within fluvial sediments. In the Upper Tisza Basin, this perspective strengthened the management relevance of preventing plastic leakage at source, because repeated accumulation and remobilisation of plastic in upstream channels and riparian zones may intensify both ecological and hydromorphological impacts over time. From a governance perspective, the practical implications of the present study are consistent with recent freshwater-plastic policy research. Y. Shi *et al*. (2024) concluded that effective freshwater plastic governance should integrate source reduction, recycling and substitution measures, monitoring and evaluation, and direct

pollution-control actions. This comparison aligns closely with the Upper Tisza Basin findings, which indicated that no single intervention would be sufficient in mountain-border municipalities. Instead, the most environmentally relevant management approach combined terrain-sensitive infrastructure planning, more reliable service schedules, local monitoring of leakage-prone river corridors and integration of community-led initiatives into formal waste-management arrangements. From a broader legal perspective, recent international-law analysis also shows that fragmented regulatory frameworks still hinder coordinated responses to cross-border plastic pollution, which reinforces the need for basin-scale cooperation in transboundary river systems (Shi & Zhang, 2026).

In general, the comparison with the literature confirmed that the effectiveness of plastic waste collection in the Upper Tisza Basin should be interpreted as a preventive mechanism for environmental safety. In this context, improving collection systems in the upstream areas of the river would not only support better efficiency of municipal waste management services but also reduce risks to river ecosystems, decrease the transport of plastic waste downstream, and contribute to more effective transboundary environmental governance. This, in turn, could lead to a reduction in the ecological burden on river ecosystems, contribute to the improvement of water resources, and decrease the negative impact of plastic pollution on biodiversity in transboundary reservoirs.

**Conceptual model for assessing plastic waste collection efficiency in mountain-border regions**

The findings of the study provided the basis for the formulation of a conceptual model for assessing plastic waste collection efficiency in mountain-border regions under conditions of environmental vulnerability and transboundary riverine risk. Unlike conventional urban-oriented waste management assessments, the proposed model integrated terrain-related accessibility constraints, institutional fragmentation and community-based adaptive mechanisms into a unified analytical structure. The conceptual model was based on four interrelated dimensions identified through the combined quantitative, geospatial and qualitative assessment conducted in the Ukrainian section of the Upper Tisza Basin: infrastructure availability, spatial accessibility, institutional-logistical capacity and community participation support. Infrastructure availability reflected the density and territorial distribution of designated plastic collection points and decentralised collection hubs. Spatial accessibility described the practical reachability of collection infrastructure under conditions of dispersed settlements, slope constraints and road-network limitations. Institutional-logistical capacity captured the regularity of collection services, route feasibility, operator coordination and municipal implementation capacity. Community participation support reflected the presence of local clean-up actions, decentralised recovery practices and outreach activities that improved practical waste recovery in underserved settlements.

At the operational assessment stage, the quantitative indicators integrated into the composite municipal efficiency index (PWCE) were aggregated using equal weights, as no validated empirical basis for differentiated weighting across municipalities was available in the analysed dataset. This approach reduced the risk of introducing subjective weighting bias and ensured methodological transparency. At the same time, the conceptual model recognised that the four dimensions did not function independently. Institutional and logistical weaknesses could reduce the practical effectiveness of available infrastructure, while low spatial accessibility could weaken community participation in routine separate collection despite local awareness efforts. Conversely, active community initiatives could partially compensate for deficiencies in infrastructure and collection frequency in remote settlements. The model also incorporated seasonal variability as a modifying influence on system performance. Tourist peaks in mountain municipalities increased temporary plastic waste generation and placed additional pressure on collection infrastructure, while spring floods and heavy precipitation increased the likelihood of mobilising accumulated plastic waste from floodplains, riverbanks and informal dumping sites. In the proposed model, these seasonal factors acted as amplifiers of existing infrastructure and governance weaknesses rather than independent determinants of efficiency.

A key feature of the model was the explicit linkage between municipal collection efficiency

and environmental safety outcomes. In mountain-border river basins, deficiencies in any of the four dimensions could increase plastic leakage into tributaries and main river channels, thereby contributing to cumulative downstream ecological risks and transboundary pollution pressures. For this reason, the model interpreted plastic waste collection efficiency not only as a municipal service-performance characteristic but also as a preventive environmental safety parameter. The proposed conceptual model could support comparative assessment across municipalities and guide prioritisation of interventions in mountain-border regions. Its practical application enabled the identification of bottlenecks in infrastructure placement, route accessibility, institutional coordination and local adaptive capacity, thereby supporting more targeted and environmentally relevant waste management planning in transboundary basin systems (Fig. 1).

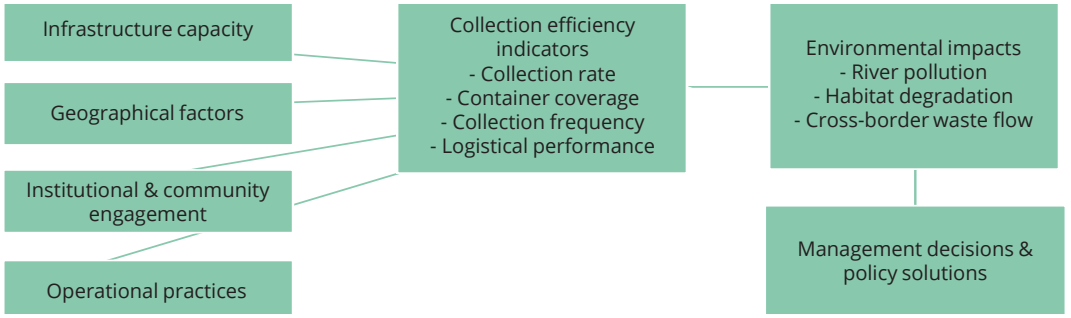


**Figure 1.** Conceptual model for assessing plastic waste collection efficiency in mountain-border regions

**Source:** developed by the authors

The conceptual model integrated the main findings of the study into a coherent analytical framework showing that plastic waste collection efficiency in mountain-border regions depended on the interaction of infrastructure availability, spatial accessibility, institutional-logistical capacity and community participation support. It also demonstrated that seasonal pressures and hydrological dynamics amplified pre-existing system weaknesses and increased the environmental significance of local collection deficits. Overall, the model provided a structured basis for interpreting the empirical results and for identifying priority directions for more effective and environmentally oriented waste management planning in transboundary basin regions.

## CONCLUSIONS

This study assessed the efficiency of plastic waste collection systems in the Ukrainian section of the Upper Tisza Basin as a mountain-border region characterised by complex terrain, dispersed settlements and transboundary environmental vulnerability. The results confirmed that municipal collection performance was determined by the combined influence of infrastructure availability, spatial accessibility, logistical feasibility and institutional capacity. The most pronounced disparities were identified between lowland and mountainous municipalities. Lower collection rates, weaker infrastructure coverage and reduced service frequency in mountainous communities were associated with terrain-related constraints, limited road accessibility and organisational fragmentation. These factors reduced the practical effectiveness of formal collection systems and increased the risk of unmanaged plastic accumulation in residential and river-adjacent areas. The study confirmed that municipal collection inefficiencies in upstream territories had direct environmental-safety implications. Insufficient plastic waste collection coverage and irregular servicing increased the probability of riverine plastic leakage, particularly during flood periods and heavy rainfall. In the Upper Tisza Basin, such leakage represented not only a local waste-management problem but also a transboundary risk affecting downstream river ecosystems.

Community-driven initiatives demonstrated an important complementary role in improving plastic waste recovery in underserved municipalities. Their practical contribution was greatest in mountainous settlements with infrastructural and logistical deficits; however, the findings also showed that such initiatives were most effective when integrated with stable municipal collection services rather than operating as isolated measures. The proposed assessment framework and conceptual model provided a structured basis for evaluating plastic waste collection efficiency in mountain-border regions exposed to riverine pollution risks. Their practical application may support terrain-sensitive infrastructure planning, seasonal service adaptation, stronger inter-municipal coordination and integration of community-based measures into environmental safety-oriented waste-management strategies.

This study had several limitations. Municipal statistical data were not uniformly available across all communities, which restricted the depth of temporal comparison. Seasonal fluctuations related to tourism intensity and hydrological conditions may also have influenced waste generation patterns and short-term efficiency indicators. In addition, the absence of long-term continuous monitoring data limited the assessment of multi-year performance trends. Nevertheless, the combination of statistical analysis, geospatial modelling and qualitative assessment ensured sufficient analytical consistency for identifying the principal determinants of plastic waste collection efficiency in the study area. The prospects for further research in this area lie in the development and implementation of integrated waste management models that take into account seasonal fluctuations, local infrastructure limitations, and transboundary ecological risks to improve waste collection efficiency in mountain-border regions.

## ACKNOWLEDGEMENTS

None.

## FUNDING

None.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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## Оцінка ефективності систем збору пластикових відходів у гірських та прикордонних регіонах: дослідження басейну Верхньої Тиси

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**Анотація.** Гірські та прикордонні регіони стикаються з вираженими труднощами в організації ефективного збору пластикових відходів через складний рельєф, розсіяні поселення та обмежену інфраструктурну спроможність. Ці труднощі особливо критичні в транскордонних річкових басейнах, де неправильне управління пластиковими відходами створює накопичувальні екологічні ризики вниз за течією. Басейн Верхньої Тиси, що належить Україні та кільком країнам Європейського Союзу, є високоризиковою зоною для транспортування пластику в річках і транскордонного забруднення. Метою цього дослідження була оцінка ефективності регіональних систем збору пластикових відходів у гірських та прикордонних умовах і визначення ключових факторів, які визначають ефективність системи. Дослідження базувалося на змішаному підході, що поєднував статистику муніципальних відходів, аналіз геопросторової доступності, польові спостереження та якісну оцінку на основі муніципальних документів і публічно доступних операційних звітів. Ефективність системи оцінювали за допомогою кількісних показників, включаючи рівень збору пластику на душу населення, покриття контейнерами, частоту збору та логістичну ефективність з урахуванням рельєфу. Результати виявили значні просторові відмінності в ефективності збору. Низовинні муніципалітети досягли рівня збору пластику 9,8-12,3 кг на особу на рік, тоді як гірські муніципалітети збирали лише 3,2-5,7 кг на особу на рік. У гірських районах менше ніж 50 % жителів мали доступ до пунктів збору в межах 300 м, порівняно з понад 80 % у низовинних поселеннях. Логістична неефективність у високогірних муніципалітетах була більш ніж удвічі вищою через поганий доступ до доріг та зміни висоти. Ініціативи, спрямовані на залучення громади, включаючи децентралізовані пункти збору та програми прибирання річок, підвищували локальну ефективність збору до 30 % у недостатньо обслуговуваних районах. Результати показали, що для покращення збору пластикових відходів у гірських та прикордонних регіонах необхідні інтегровані рішення, які поєднують оптимізацію інфраструктури, логістику, чутливу до рельєфу, інституційну координацію та залучення громади. Запропонована система оцінки може бути застосована в інших транскордонних гірських регіонах для підвищення екологічної безпеки та сталого використання ресурсів

**Ключові слова:** управління пластиковими відходами; просторовий доступ; прикордонні території; річкове забруднення; ефективність збору; управління річковими басейнами; екологічна безпека