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Article

Mapping and Quantifying Mine Waste Dump Expansion in the Katangan Copperbelt (Democratic Republic of the Congo): Implications for Ecological Remediation

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Abstract

The rapid expansion of mining activities in the Katangan Copperbelt has led to the accumulation of large volumes of mine waste dumps, which increasingly structure extractive landscapes. However, their spatial dynamics and morphological evolution remain insufficiently documented. This study analyses the spatio-temporal evolution of mine waste dumps in Lualaba Province (Democratic Republic of the Congo) between 2009 and 2025 in order to characterize their growth patterns, morphological changes, and spatial organization. Mine waste dumps were mapped through multi-temporal interpretation of high-resolution imagery in Google Earth Pro and analysed using GIS-based spatial metrics and statistical approaches. Results reveal a strong increase in dump area from approximately 1,900 ha in 2009 to more than 6,400 ha in 2025. The dynamics shift from a phase dominated by the proliferation of dumps between 2015 and 2020 to a phase characterized by the expansion and consolidation of existing deposits after 2020. Mutshatsha territory emerges as the main hotspot of mining intensification, while Lubudi territory displays more irregular dynamics and stronger morphological changes. Spatial metrics indicate a clustered distribution of dumps around active mining areas, followed by a partial spatial expansion toward new zones after 2020. Although most dumps occur relatively close to the road network, statistical analyses show that transport accessibility has only a limited influence on their size or emergence. Overall, these results highlight the importance of morpho-spatial monitoring of mine waste dumps for understanding mining landscape transformations and for supporting the spatial prioritization of ecological remediation strategies.

Keywords: mine tailings; spatial dynamics; landscapes ecology; patch morphology; extractive intensification; Katangan copper belt; GIS

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1. Introduction

The contemporary intensification of mining represents one of the most significant territorial transformations of the past two decades [1]. Driven by rising demand for strategic metals associated with the energy transition and digitalization, this expansion has resulted in increasing extraction volumes, the proliferation of mining infrastructures, and a substantial growth in the production of waste materials [2]. These dynamics are embedded within broader processes of land system change,

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whereby globalized economic pressures reconfigure land-use systems across multiple scales [3]. Extractive landscapes therefore constitute the spatial expression of intensified material flows, revealing the socio-economic metabolisms underpinning contemporary resource systems [4].

Existing research has largely documented these transformations through analyses of mining footprint expansion, deforestation, and habitat fragmentation [5]. Medium-resolution multispectral imagery (e.g., Landsat, Sentinel) has enabled the quantification of artificial surface expansion at regional scales [6]. However, such approaches remain limited for the specific characterization of mine waste dumps. Their spatial resolution (10–30 m) often aggregates heterogeneous components of mining complexes within generic classes (e.g., "mine" or "bare soil"), hindering the differentiation between pits, operational platforms, and mine waste dumps [7]. Spectral similarities may also generate confusion with bare agricultural soils or degraded surfaces, particularly in seasonally variable tropical environments [8]. Moreover, these methods primarily provide surface-based estimates and fail to capture the internal morphology and spatial structuring of mine waste dumps, thereby constraining volumetric and geomorphological assessments [9,10].

In situ approaches offer high precision for estimating volumes and geotechnical properties through topographic surveys, drilling campaigns, and high-resolution digital terrain models [11,12]. Yet their spatial coverage remains limited, implementation costs are substantial, and access to industrial datasets is often restricted in strategic mining contexts [13]. Furthermore, the lack of systematic historical topographic records hampers the diachronic reconstruction of morphological trajectories at broader territorial scales [14].

Consequently, the spatial structuring of mine waste dumps remains only partially understood, despite their role as the direct material expression of extractive flows. Within the framework of anthropogenic geomorphology, such mine waste dumps can be interpreted as artificial geomorphological landforms whose growth, complexity, and spatial distribution reflect the intensity and organization of mining systems [14]. Their analysis therefore extends beyond surface quantification to address patterns of spatial aggregation, diffusion, and polarization of material accumulations, in line with metabolic perspectives on socio-ecological systems [4]. From a remediation perspective, understanding the spatial configuration and morphological evolution of mine waste dumps is essential for designing effective restoration strategies. The spatial concentration, size, and geometry of mine waste dumps influence erosion risks, contaminant dispersion, and the feasibility of ecological rehabilitation. Identifying priority zones for stabilization, revegetation, or containment therefore requires spatially explicit analyses of mining waste landscapes. Despite this relevance, spatial monitoring approaches remain underdeveloped in many mining regions of the Global South.

High-resolution multi-temporal photo-interpretation provides a particularly suitable methodological alternative for analysing mine waste dumps [15]. Mine waste dumps exhibit distinctive visual characteristics—homogeneous texture, anthropogenic morphology, and sparse vegetation cover—that allow accurate delineation from very high-resolution imagery. In this study, the analysis relies on multi-temporal satellite images available through Google Earth Pro, which provides access to sub-meter resolution imagery from multiple commercial providers. This archive enables consistent visual interpretation of mining features across time while offering sufficient spatial detail to identify and delineate mine waste dumps with high precision. Previous studies have demonstrated the robustness of Google Earth–based photo-interpretation for mapping anthropogenic landforms and land-use changes in data-constrained environments [16,17]. Combined with landscape metrics derived from landscape ecology and morphometric analysis [18,19], this approach enables the simultaneous assessment of surface extent, morphological complexity, and spatial organization—dimensions that remain rarely integrated in studies of African mining landscapes [20].

The Central African Copperbelt, extending across the Democratic Republic of the Congo and Zambia, is one of the world's most significant metallogenic Provinces. Within this system, the Katangan Copperbelt encompasses the Provinces of Haut-Katanga and Lualaba, where some of the

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richest copper–cobalt deposits are concentrated. Within this corridor, Lualaba Province represents a strategic case study. The Democratic Republic of the Congo supplies more than 70% of global cobalt production and ranks among the leading copper producers worldwide, making the region central to critical mineral supply chains supporting the energy transition [21]. Since the early 2010s, mining activity has expanded rapidly in response to rising demand for batteries and low-carbon energy infrastructures [22]. New mine waste dumps and the expansion of existing operations—particularly around Kolwezi—have driven sustained increases in extraction volumes and accelerated waste accumulation, producing visible morphological transformations of the landscape [23–25]. The coexistence of industrial mining and artisanal and small-scale mining (ASM) generates heterogeneous spatial configurations influencing the formation of mine waste dumps [26]. This hybrid mining landscape makes Lualaba a relevant laboratory for analysing the spatial aggregation and polarization of mining accumulations, yet detailed morpho-spatial assessments remain scarce [5].

This study investigates the spatio-temporal dynamics and morphological reconfiguration of mine waste dumps in Lualaba between two distinct time points to determine whether observed changes correspond to simple quantitative expansion or to a structured transformation of the extractive landscape. Specifically, the analysis examines: (i) whether growth primarily results from the expansion of existing structures or from the emergence of new mine waste dumps; (ii) whether spatial patterns reflect territorial concentration or diffusion; and (iii) whether morphological complexity increases over time. Because mine waste dumps are typically expanded around existing disposal infrastructures rather than establishing entirely new sites, spatial growth is expected to occur primarily through the enlargement of existing dumps. Such processes generally lead to increased morphological complexity, as expanding dumps progressively develop irregular boundaries. Based on this reasoning, we hypothesize that the observed increase in waste dump area is mainly driven by the enlargement of existing dumps rather than by the creation of new ones.

2. Materials and Methods

2.1. Study Area

The Lualaba Province (Figure 1), located in southeastern Democratic Republic of the Congo, lies at the core of the Katangan Copperbelt, one of the world’s major metallogenic Provinces for copper and cobalt [23]. The landscape is characterized by gently undulating plateaus (1,000–1,500 m) dissected by a dense hydrographic network belonging to the Lualaba basin. Vegetation is dominated by miombo woodlands, interspersed with grassy savannas and expanding agricultural areas [27]. The sub-humid tropical climate with a marked dry season (Köppen–Geiger Cw) promotes active soil erosion; consequently, exposed surfaces—particularly mine waste dumps—are highly vulnerable to runoff and sediment dispersion [28]. Within this biophysical context, Lualaba has become a strategic extractive hub in Central Africa, accounting for a significant share of national copper and cobalt production and supplying global energy transition value chains [23]. Recent investments in transport and logistics infrastructure, notably linked to the Lobito Corridor connecting the mining hinterland to Angolan Atlantic ports, are strengthening regional mineral flows while intensifying pressures on extractive territories [29,30]. Within Lualapa Province, this study focuses on Mutshatsha and Lubudi territories, selected for their high mining intensity and the diversity of exploitation regimes, where industrial and artisanal mining activities coexist [26]. Mutshatsha territory is dominated by large industrial concessions and key transport infrastructure, forming a major logistical node. Lubudi territory, in contrast, combines industrial and artisanal mining, generating diverse accumulation dynamics and waste-dump structures. This territorial complementarity provides a comparative framework for analysing differentiated spatial reconfigurations of extractive landscapes within an intensifying regional mining system [31].

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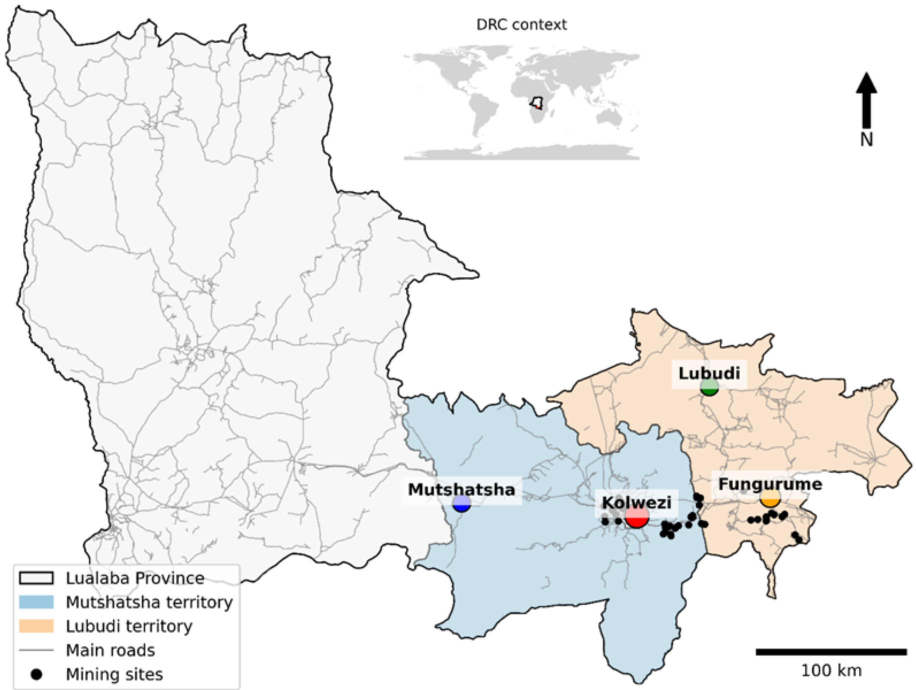

Figure 1. Location of the study area in Lualaba Province (Democratic Republic of the Congo). The map shows the boundaries of Lualaba Province, and the two territories analysed in this study (Mutshatsha and Lubudi). The predominantly agricultural territories of Sandoa, Kapanga and Dilolo were excluded from the analysis. The map also displays the main road network and mining sites derived from the Global Mining Areas dataset. Urban centers (Kolwezi, Fungurume, Mutshatsha and Lubudi) are represented by proportional colored symbols. The inset map indicates the location of Lualaba Province within the Democratic Republic of the Congo. Data source: Global Mining Areas dataset [5].

2.2. Data and Temporal Framework

This study is based on a vector database of mine waste dumps produced through multi-temporal photo-interpretation of high-resolution imagery available in Google Earth Pro [32]. This platform was selected because it provides access to mosaics of very high-resolution satellite imagery as well as the Historical Imagery tool, which enables the examination of landscape evolution across different dates—an essential feature for diachronic analyses of mining landscapes [33]. Four reference years structure the analysis: 2009, 2015, 2020, and 2025. This temporal framework spans more than fifteen years of landscape transformations in Lualaba Province and corresponds to different phases in the development of the mining sector.

The study period falls within the broader context of the liberalization of the mining sector initiated by the Mining Code of 2002, which facilitated the arrival of new foreign investments in the Congolese Copperbelt. The year 2009 corresponds to the recovery phase following the global financial crisis, marked by the redeployment of capital—particularly Chinese investments—into the region. The year 2015 coincides with the creation of Lualaba Province following the territorial reform and with a notable intensification of mining activities. The years 2020 and 2025 represent the most recent phase, characterized by rising global demand for copper and cobalt associated with the energy transition, as well as the continued expansion of investments in the extractive sector [31].

For each reference year, images acquired during the dry season, exhibiting comparable spatial resolution and minimal cloud cover, were selected to ensure reliable interpretation in tropical environments. This seasonal consistency helps minimize biases related to vegetation phenology, soil moisture, or shadow effects, thereby ensuring diachronic comparability across the different observation dates [31].

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Mine waste dumps were identified based on distinctive visual signatures, including relatively coarse texture, light to brownish coloration, anthropogenic morphology (slopes, benches, and ridge lines), and sparse or absent vegetation cover. These characteristics are commonly used in studies of Anthropogeomorphology and mining-related remote sensing to distinguish mine waste dumps from other bare surfaces [34]. The use of high-resolution imagery is particularly important in this context, as it enables reliable differentiation between mine waste dumps and other exposed surfaces such as agricultural fields, fallow land, or temporary construction sites, which remain difficult to discriminate using medium-resolution multispectral imagery such as Landsat or Sentinel [5,35].

2.3. Database Construction: Stakeholder Consultation, Field Observations, and Digitisation

Prior to the mapping phase, consultations were conducted in late June 2025 with nine officers from the Provincial Division of Mines of Lualaba Province to identify the main industrial operators involved in the management of mine waste dumps and to locate areas likely to contain mine waste dumps. The involvement of local stakeholders constitutes an important step in improving the contextual relevance of spatial analyses and strengthening the quality of information produced in complex socio-ecological systems [36].

Field missions carried out between July and August 2025 in the territories of Mutshatsha and Lubudi enabled the direct documentation of the morphology and spatial organization of mining waste dumps. Observations focused on the characteristic forms of the mine waste dumps (slopes, benches, and ridge lines), their surface textures, and their spatial relationships with mining infrastructures such as extraction pits, processing platforms, settling ponds, and access roads. These observations helped refine and validate the criteria used for photo-interpretation, in accordance with field validation principles commonly applied in remote sensing studies [36].

Based on these field observations, a standardized interpretation key was developed using georeferenced photographs and detailed field notes. Mine waste dumps were identified according to several visual and contextual criteria: recognizable anthropogenic morphology, relatively homogeneous or coarse surface texture, sparse vegetation cover, spatial association with mining infrastructures, and temporal persistence across multiple image dates. The combined use of these criteria reduces potential confusion with other exposed surfaces such as agricultural fallow land, degraded soils, or temporary construction sites. Similar approaches relying on visual interpretation of high-resolution imagery have been widely applied for mapping mining waste and spoil heaps in various geographical contexts [5,34].

Manual digitization of the mine waste dumps was subsequently performed in Google Earth Pro at mapping scales ranging from 1:2,000 to 1:5,000 to accurately delineate often complex boundaries [38]. Each mine waste dump was treated as a distinct morphological entity when topographic and functional continuity could be clearly established. A minimum mapping unit of 0.25 ha was applied to limit artifacts associated with small-scale surface disturbances. The adoption of a minimum mapping threshold consistent with image resolution and the target landform contributes to stabilizing spatial estimates and improving the repeatability of measurements [39].

After digitization, the polygons were exported to a geospatial analysis environment [40], based on Python and reprojected into the coordinate reference system WGS 84 / UTM Zone 35S. This metric projection enables precise calculations of areas, perimeters, and distances. Spatial processing was conducted using dedicated geospatial libraries, including GeoPandas for vector data manipulation and NumPy and Pandas for statistical operations.

2.3. Spatio-Temporal Analysis of Mine Waste Dump Dynamics

The spatial dynamics of mine waste dumps were analysed through a multi-temporal comparison of vector datasets corresponding to the years 2009, 2015, 2020, and 2025. Geometric overlay operations were used to identify the evolutionary trajectories of dumps between successive observation dates. Four categories of spatial trajectories were distinguished: (1) persistent surfaces, present at both dates; (2) extension areas, corresponding to the enlargement of existing dumps; (3)

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newly formed dumps, appearing during the subsequent observation period; and (4) losses or transformations, corresponding to dumps that disappeared or were converted to other land-cover types [41,42]. For each time interval (2009–2015, 2015–2020, and 2020–2025), the surface areas associated with these categories were calculated to characterize the trajectories of mining waste expansion. Multi-temporal object-based approaches of this type are widely used to analyse the evolution of mining footprints derived from satellite imagery [5].

To quantify these dynamics at the landscape scale, three complementary landscape metrics were calculated: Class Area (CA), Patch Number (PN), and Mean Patch Size (MPS) [43,44]. CA corresponds to the cumulative area occupied by all dumps and reflects the overall spatial footprint of mining waste disposal. Increasing CA values indicate a global expansion of the dumping system and therefore a growing environmental footprint requiring larger-scale remediation or containment interventions [19,45]. PN represents the total number of individual dumps and captures the degree of spatial fragmentation of the dumping system. Increasing PN values indicate the emergence of additional disposal sites and therefore a spatial dispersion of contaminated surfaces that may complicate remediation efforts by multiplying the number of sites requiring stabilization or restoration [46,47]. Mean Patch Size (MPS), calculated as the ratio between total dump area and patch number, represents the average size of individual dumps. Increasing MPS values indicate that dumps are becoming larger on average and therefore suggest expansion through the enlargement of existing dumps, which may facilitate remediation through targeted stabilization or containment measures. Conversely, decreasing MPS values indicate the proliferation of smaller dumps, implying the need for broader landscape-scale rehabilitation strategies [48].

The Largest Patch Index (LPI) was used to evaluate the spatial dominance of large dumps within the mining landscape. LPI measures the proportion of the total dump area occupied by the largest individual deposit. Increasing LPI values indicate that mining waste becomes increasingly concentrated within a limited number of large dumps, which may represent priority targets for remediation actions such as containment, stabilization, or phytostabilization. Conversely, stable or decreasing LPI values indicate a more distributed spatial structure in which remediation efforts may need to be implemented across multiple smaller sites [49,50].

The geometric morphology of mine waste dumps was assessed using the Shape Index (SI), which quantifies the degree of boundary irregularity of individual dumps. Higher SI values indicate more irregular boundaries and therefore greater morphological complexity of dump shapes. Such complexity increases the interface between waste materials and surrounding land surfaces and may enhance the risks of erosion, sediment transport, or contaminant dispersion. Consequently, increasing SI values may highlight areas where erosion control, surface stabilization, or revegetation measures are particularly needed. Shape-based metrics of this type are widely used to characterize the geometric complexity of mapped landscape features [52,53].

The structural configuration of dumps within the mining landscape was further described using Edge Density (ED), defined as the ratio between the total length of dump boundaries and the total area analysed. ED quantifies the intensity of interfaces between waste dumps and surrounding land surfaces. Increasing ED values indicate a greater exposure of contaminated materials to surrounding ecosystems, potentially increasing the risks of pollutant dispersion and environmental degradation. Such conditions may require enhanced monitoring and targeted remediation interventions aimed at stabilizing dump margins or reducing surface runoff [53,54].

The spatial organization of dumps was analysed using a nearest-neighbour approach. The mean nearest-neighbour distance between dump centroids was calculated to evaluate the degree of spatial aggregation or dispersion within the mining landscape. Decreasing nearest-neighbour distances indicate increasing spatial concentration of dumps around mining activity zones, which may lead to cumulative environmental pressures on nearby ecosystems and therefore require prioritized remediation efforts in these hotspots [55,56]. To further characterize spatial patterns, the Clark and Evans aggregation index (R) was calculated by comparing the observed mean nearest-neighbour distance with the expected distance under a random spatial distribution. Values of $R < 1$ indicate

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clustering of dumps, values close to R = 1 indicate random spatial patterns, and values R > 1 indicate a regular spatial arrangement [57]. In addition, the distribution of nearest-neighbour distances was analysed to detect potential changes in spatial dispersion through time.

Finally, the influence of transport accessibility on the spatial organization of mine waste dumps was evaluated by calculating the Euclidean distance between each dump centroid and the nearest road segment. The relationship between dump size and road proximity was analysed using Spearman's rank correlation and ordinary least squares (OLS) regression. A negative relationship between dump area and distance to roads would indicate that larger dumps tend to occur closer to transport infrastructure, suggesting that accessibility plays a key role in dump expansion [58,59]. From a remediation perspective, such proximity may facilitate the logistical implementation of stabilization or restoration measures. In addition, a binary logistic regression model was used to test whether the probability of new dump formation decreases with increasing distance from the road network, providing insights into how infrastructure accessibility may influence both the expansion and potential management of waste disposal sites [60,61].

3. Results

3.1. Expansion of the Mining Waste Footprint

The spatial footprint of mine waste dumps expanded markedly between 2009 and 2025 across Lualaba Province and its main mining territories (Table 1). At the provincial scale, the total area occupied by mine waste dumps (CA) increased from 1,916 ha in 2009 to 6,432 ha in 2025, representing more than a threefold increase over the study period. This expansion was accompanied by a substantial rise in the number of dumps (PN), which increased from 53 to 105 deposits, indicating an intensification of waste accumulation associated with mining activities.

Changes in the mean patch size (MPS) and the largest patch index (LPI) reveal important shifts in the spatial structure of dumps. While the mean size of dumps increased from 36.15 ha to 61.26 ha, the dominance of the largest deposit declined between 2009 and 2020 (LPI decreasing from 26% to 11%) before slightly increasing again by 2025. This pattern suggests an initial diffusion of mining waste deposits through the creation of multiple dumps, followed by a phase characterized by the expansion of existing structures, leading to larger average dump sizes.

Similar dynamics are observed at the territorial level, although with notable contrasts between Mutshatsha and Lubudi (Table 1). Mutshatsha territory concentrates most of the mining waste footprint, with dump area increasing from 1,579 ha in 2009 to 4,589 ha in 2025, accompanied by an increase in the number of deposits from 30 to 68. The increase in mean patch size to 67.48 ha in 2025 indicates that expansion processes became increasingly dominant in this territory during the later phases of the study period.

In contrast, Lubudi territory exhibits a more irregular trajectory. The dump area increased from 246 ha in 2009 to 801 ha in 2015, then slightly declined in 2020 before rising again to 1,620 ha in 2025. Although the number of dumps increased progressively from 20 to 34, their mean size remained smaller than in Mutshatsha, suggesting a more fragmented configuration of waste deposits.

Table 1. Evolution of mine waste dump spatial metrics in Lualaba Province and its main territories between 2009 and 2025. The table presents the temporal evolution of key landscape metrics describing the spatial extent and configuration of mining waste dumps at different spatial scales (province and territories). CA (Class Area) represents the total area occupied by mine waste dumps (ha); PN (Patch Number) corresponds to the number of individual dumps identified in each spatial unit; MPS (Mean Patch Size) indicates the average area of dumps (ha); and LPI (Largest Patch Index) expresses the proportion of the total dump area occupied by the largest deposit (%), reflecting the degree of spatial dominance of the largest mining waste structure within the landscape.

Spatial scale	Year	CA	PN	MPS	LPI (%)
	2009	1916.12	53	36.15	26.00

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Lualaba Province	2015	2925.34	70	41.79	17.00
	2020	4054.88	98	41.38	11.00
	2025	6432.06	105	61.26	14.00
Mutshatsha territory	2009	1579.97	30	52.67	32.00
	2015	2017.11	44	45.84	25.00
	2020	3199.74	63	50.79	14.00
	2025	4588.60	68	67.48	19.00
Lubudi territory	2009	246.13	20	12.31	17.00
	2015	801.14	24	33.38	33.00
	2020	701.38	32	21.92	17.00
	2025	1620.49	34	47.66	12.00

The decomposition of growth trajectories further clarifies these dynamics (Table 2). At the provincial scale, large portions of the mining waste footprint persisted through time, with 1,621 ha of persistent dumps between 2009 and 2015 and 3,324 ha between 2020 and 2025, indicating the long-term stability of major disposal sites. However, the analysis also highlights strong contributions from the emergence of new dumps. For example, between 2015 and 2020, 1,987 ha of new deposits corresponding to 42 dumps appeared, illustrating an intense phase of spatial diffusion of mining waste.

During the most recent period (2020–2025), growth was increasingly driven by the expansion of existing dumps, which accounted for 2,377 ha, while the number of expansion events remained relatively limited (7 dumps). This indicates that large deposits expanded significantly during this phase rather than numerous new dumps being created.

At the territorial level, Mutshatsha shows a similar transition from diffusion to consolidation. Between 2015 and 2020, the creation of 27 new dumps representing 1,511 ha played a major role in the growth of the mining waste footprint. In contrast, between 2020 and 2025, expansion processes dominated, with 1,387 ha of enlargement affecting only five dumps, reflecting the intensification of already established disposal sites.

Lubudi displays a distinct dynamic. Between 2015 and 2020, no expansion of existing dumps was detected, while 399 ha of new deposits appeared and 506 ha were lost or transformed, suggesting strong spatial turnover of waste disposal sites. In the following period (2020–2025), growth resumed primarily through the expansion of a limited number of deposits, representing 918 ha across only two dumps, alongside the creation of 1,148 ha of new deposits.

These different trajectories are illustrated by representative examples derived from high-resolution imagery (Figure 4). Persistent dumps correspond to long-established disposal sites that remain present across several years, while loss processes reflect the disappearance or transformation of previously active dumps. New deposits illustrate the emergence of waste disposal areas linked to new mining operations, whereas expansion processes correspond to the progressive enlargement of existing dumps as material accumulation increases over time.

Overall, these results highlight a rapid and spatially heterogeneous expansion of the mining waste footprint in Lualaba Province, driven by a combination of dump proliferation and enlargement of existing deposits, with distinct trajectories between the major mining territories.

Table 2. Decomposition of mine waste dump growth trajectories in Lualaba Province and its main territories between 2009 and 2025. Persistent area corresponds to dumps maintained between two dates; Expansion indicates the enlargement of existing dumps; New refers to newly created dumps; and Loss represents dumps that disappeared or were transformed. Values are expressed as surface area (ha), with the number of dumps indicated in parentheses (n).

Site	Period	Persistent_area_ha (n)	Expansion_ha	New_ha	Loss_ha
Lualaba	2009-2015	1621.44 (37)	1009.22 (17)	1303.90 (33)	294.68 (16)
Lualaba	2015-2020	2067.47 (56)	1129.55 (28)	1987.42 (42)	857.87 (14)

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Lualaba	2020-2025	3323.90 (79)	2377.18 (7)	3108.17 (26)	730.99 (19)
Mutshatsha	2009-2015	1320.17 (22)	434.91 (14)	675.57 (22)	240.67 8)
Mutshatsha	2015-2020	1657.75 (36)	1173.43 (19)	1511.42 (27)	338.00 (8)
Mutshatsha	2020-2025	2737.39 (55)	1386.66 (5)	1818.44 (13)	431.78 (8)
Lubudi	2009-2015	204.95 (12)	555.01 (4)	596.19 (12)	41.18 (8)
Lubudi	2015-2020	294.90 (18)	0.00 (0)	399.10 (22)	506.24 (6)
Lubudi	2020-2025	463.98 (23)	918.45 (2)	1148.47 (11)	230.02 (9)

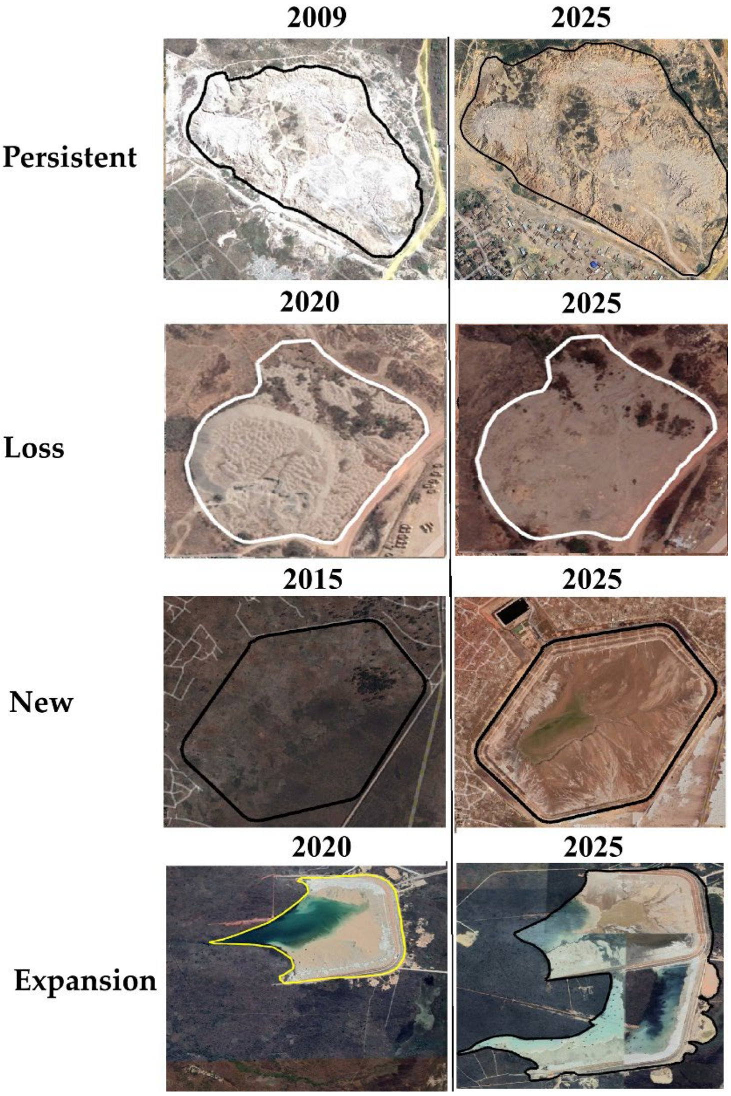

Figure 4. Examples of spatio-temporal trajectories of mine waste dumps in Lualaba Province derived from multi-temporal interpretation of high-resolution imagery (Google Earth Pro). Four typical processes are illustrated: Persistent dumps remaining present across dates (2009–2025); Loss, corresponding to dumps that disappeared or were transformed (2020–2025); New, representing dumps that emerged between two dates (2015–2025); and Expansion, indicating the enlargement of an existing dump (2020–2025). Polygon outlines highlight the extent of the dumps used for visual interpretation.

3.2. Morphological Evolution of Mine Waste Dumps

The morphological characteristics of mine waste dumps evolved moderately between 2009 and 2025, reflecting changes in the spatial configuration and geometric complexity of deposits across Lualaba Province and its main territories (Table 3).

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At the provincial scale, edge density decreased progressively from 63.85 m/ha in 2009 to 52.13 m/ha in 2025, indicating a gradual reduction in the relative length of dump boundaries compared to their total surface area. This pattern suggests that dumps became progressively more consolidated and spatially continuous, likely reflecting the expansion and coalescence of existing deposits. In contrast, the morphological complexity index remained relatively stable during the first part of the study period but increased slightly from 4.66 in 2020 to 4.88 in 2025, indicating a modest increase in boundary irregularity as dumps expanded.

At the territorial level, similar tendencies are observed but with notable differences between Mutshatsha and Lubudi. In Mutshatsha, edge density fluctuated moderately before declining from 54.07 m/ha in 2020 to 48.42 m/ha in 2025, while the complexity index increased from 4.68 to 4.81. These trends suggest that the recent growth of dumps in this territory occurred mainly through the enlargement of existing deposits, resulting in larger but still morphologically irregular structures.

In contrast, Lubudi territory displays higher edge density values throughout the study period, particularly in 2009 (126.50 m/ha), reflecting a more fragmented spatial configuration of dumps during the early phase of mining activity. Edge density subsequently declined substantially to 62.96 m/ha in 2025, indicating a progressive consolidation of deposits. At the same time, the morphological complexity index increased to 5.08 in 2025, the highest value observed in the study area, suggesting that dump expansion in Lubudi has generated increasingly irregular boundaries.

Overall, the combined evolution of edge density and morphological complexity indicates a transition from a fragmented configuration of smaller dumps toward larger and more structurally complex deposits, particularly during the most recent phase of mining expansion. These changes reflect the progressive enlargement and morphological transformation of mining waste deposits as material accumulation increases over time.

Table 3. Evolution of morphological indices of mine waste dumps in Lualaba Province and its main territories between 2009 and 2025. All indices are dimensionless. FD: fractal dimension; Compactness: compactness index; Complexity: morphological complexity index.

Spatial Scale	Year	Edge Density (m/ha)	Complexity
Lualaba Province	2009	63.85	4.68
	2015	61.52	4.69
	2020	60.37	4.66
	2025	52.13	4.88
Mutshatsha territory	2009	53.56	4.61
	2015	56.92	4.59
	2020	54.07	4.68
	2025	48.42	4.81
Lubudi territory	2009	126.50	4.85
	2015	71.98	4.84
	2020	88.92	4.60
	2025	62.96	5.08

3.3. Spatial Organization of Dumps

The spatial structure of mine waste dumps reveals a consistently clustered configuration throughout the study period (Figure 5). The Clark–Evans aggregation index remains below 1 for all years (Figure 5a), indicating that dumps are not randomly distributed but tend to occur in spatial clusters associated with mining activity areas.

The evolution of the Clark–Evans index suggests moderate temporal changes in the intensity of clustering. The lowest value observed in 2015 ($R \approx 0.41$) indicates a period of strong spatial aggregation, while the increase observed in 2025 ($R \approx 0.62$) suggests a slight reduction in clustering intensity. Despite this increase, the index remains well below 1, confirming that the spatial distribution of dumps continues to be strongly aggregated.

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Changes in the mean nearest-neighbour distance further illustrate these spatial dynamics (Figure 5b). The average distance between dumps decreased from approximately 1577 m in 2009 to around 1180 m in 2020, indicating an increasing spatial concentration of deposits. This trend reflects the progressive development of mining waste dumps around established mining sites during the expansion phase of mining activity. In contrast, the mean nearest-neighbour distance increased substantially in 2025 (approximately 2069 m), suggesting a spatial expansion of mining waste deposits toward new areas.

The distribution of nearest-neighbour distances provides additional insight into this spatial pattern (Figure 5c). The strongly right-skewed distribution indicates that most dumps occur at relatively short distances from each other, while only a small number of deposits are located at larger distances. This pattern confirms that mining waste dumps tend to form clusters around active mining operations, with occasional isolated deposits emerging in more peripheral areas.

Overall, these results highlight a spatial organization characterized by persistent clustering of mining waste dumps around mining activity centers, combined with a gradual spatial expansion toward new zones during the most recent phase of mining development..

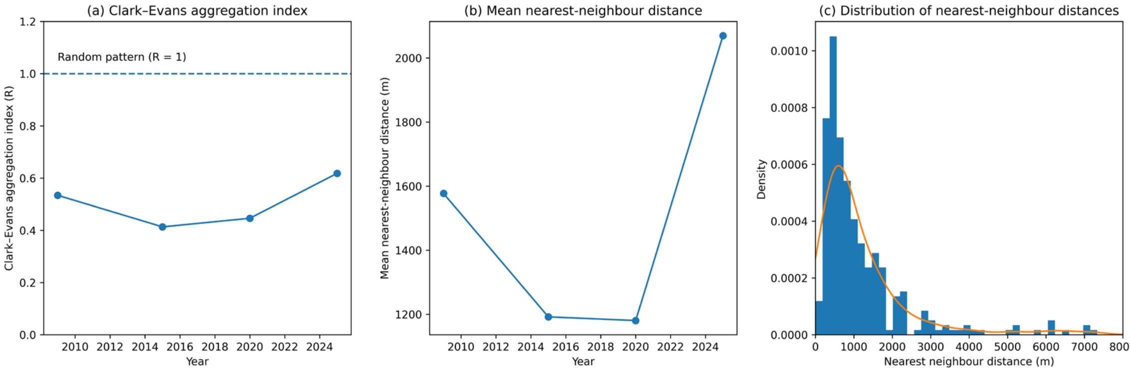

Figure 5. Spatial structure of mine waste dumps in Lualaba Province between 2009 and 2025. (a) Evolution of the Clark–Evans aggregation index (R), where values below 1 indicate spatial clustering of dumps. (b) Mean nearest-neighbour distance between dumps over time. (c) Distribution of nearest-neighbour distances, showing a strongly right-skewed pattern, indicating that most mine waste dumps occur at short distances from each other and are spatially clustered around mining activity areas.

3.4. Impact of Logistics Infrastructure

The influence of transport infrastructure on the spatial distribution of mine waste dumps was evaluated by analysing the relationship between dump characteristics and their distance to the road network. The scatter plot relating dump size to road distance (Figure 6a) reveals a weak and highly dispersed relationship between these variables. Large dumps are observed both near and far from roads, indicating that the size of deposits is not strongly constrained by road accessibility.

The distribution of dumps across distance classes (Figure 6b) shows that most deposits occur within the first distance intervals, particularly within approximately 0–2000 m of the road network, while the number of dumps decreases progressively with increasing distance. This pattern suggests that waste disposal sites tend to occur in relatively accessible areas but are not strictly limited to immediate proximity to transport infrastructure.

Statistical analyses further confirm the limited influence of road proximity on dump characteristics (Table 6). The Spearman correlation indicates a weak and non-significant relationship between dump area and distance to roads ($\varrho = -0.048$; $p = 0.388$). Similarly, the ordinary least squares regression shows extremely low explanatory power ($R^2 = 0.001$), indicating that road distance explains only a negligible proportion of the variability in dump size. The logistic regression model examining the emergence of new dumps also reveals a very weak effect of road distance on the probability of new deposit occurrence (Figure 6c; Table 6).

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Taken together, these results indicate that although many dumps are located relatively close to roads, the road network does not appear to play a dominant role in determining the size or spatial distribution of mine waste dumps. Instead, dump dynamics are more likely controlled by the spatial organization of mining activities and the location of extraction sites rather than by transport infrastructure alone.

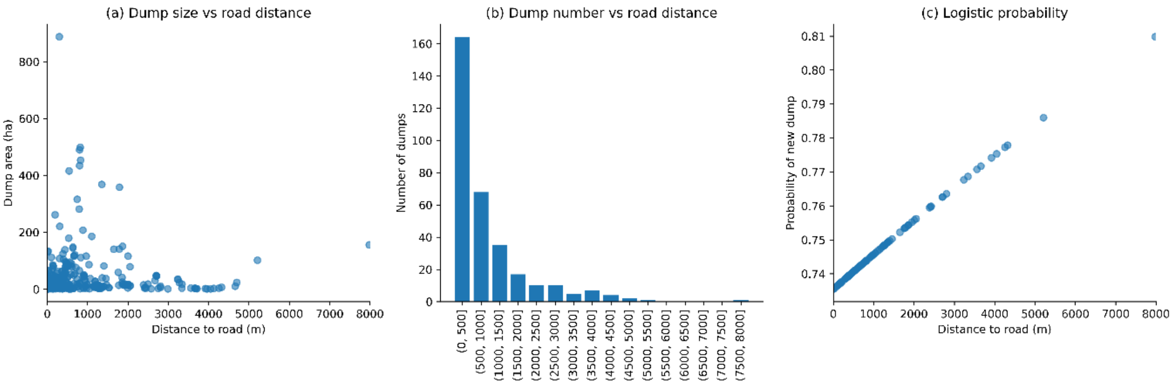

Figure 6. Figure 6. Influence of road infrastructure on the spatial distribution of mine waste dumps in Lualaba Province. (a) Relationship between dump size and distance to the nearest road. Each point represents an individual dump. (b) Distribution of dumps according to distance classes from the road network (0–8000 m). (c) Logistic regression showing the probability of new dump occurrence as a function of road distance..

Table 6. Statistical relationship between mine waste dump characteristics and distance to the road network in Lualaba Province based on Spearman correlation, ordinary least squares (OLS) regression, and logistic regression models.

Model	Dependent variable	Predictor	Coefficient	p-value	R^2
Spearman correlation	Dump area	Distance to road	−0.048	0.388	—
OLS regression	Dump area	Distance to road	−0.0028	0.53	0.001
Logistic regression	New dump occurrence	Distance to road	5.34×10^{-5}	—	—

4. Discussion

4.1. Methodological Limitations

Multi-temporal morpho-spatial analysis provides a robust framework for documenting transformations in extractive landscapes and tracking the evolution of mining infrastructures at the territorial scale. However, several methodological considerations must be acknowledged to clarify the analytical scope of the results. First, the mapping relies on visual photo-interpretation and manual digitization, which inherently depend on operator expertise and may introduce a degree of interpretative subjectivity. Nevertheless, for morphologically complex features such as mine waste dumps [62], previous research indicates that visual interpretation of very-high-resolution imagery often performs better than automated classification approaches [63], particularly in tropical environments characterized by strong radiometric variability, heterogeneous land cover, and rapid vegetation dynamics [64]. To limit potential bias, the analysis was based on a standardized interpretation key derived from field observations, explicit morphological criteria, and systematic cross-validation through the independent re-digitization of a subset of features.

Second, the diachronic mapping relies on imagery from Google Earth Pro, which aggregates images acquired by different sensors and at different dates. This heterogeneity can introduce uncertainties in temporal comparability or surface estimation [65]. These effects were minimized by selecting dry-season images with comparable spatial resolution and limited cloud cover [66]. In

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addition, the use of four observation dates spanning more than fifteen years reflects a conservative strategy designed to capture structural transformations of the extractive landscape rather than short-term fluctuations.

Finally, the absence of volumetric information limits the direct estimation of material quantities stored in waste dumps [67]. However, in landscape ecology and anthropogenic geomorphology, the morphology and spatial configuration of mine waste deposits are widely used as reliable proxies for the intensity of extractive material flows when multi-temporal elevation data are unavailable [68]. The use of established morpho-spatial metrics therefore provides a consistent basis for assessing structural reconfiguration within mining landscapes [69]. Taken together, the convergence of spatial indicators, the diachronic consistency of observed trends, and the validation procedures implemented support the robustness of the analysis and provide a reliable basis for interpreting the spatial restructuring of extractive landscapes.

4.2. Spatial Reconfiguration of Mine Waste Dumps and Territorial Regimes of Extractive Intensification in Lualaba

The extractive trajectory of Katanga reflects a long-term intensification of mining activities despite major institutional transformations. Precolonial extraction was largely artisanal, embedded in local economies, and produced limited geomorphological disturbance without large waste accumulations [70]. Industrialization in the early twentieth century under the Union Minière du Haut-Katanga reorganized extraction into a capital-intensive system integrating mechanized production, centralized processing, and transport infrastructures [71]. Post-independence nationalization and the creation of Gécamines extended this productivity model [72]. Subsequent liberalization through the 2002 Mining Code intensified extraction and waste accumulation in response to global copper and cobalt demand [73,74], consistent with trajectories documented in the Zambian Copperbelt and the Peruvian Andes [75,76].

Despite this overall intensification, the spatial dynamics of mine waste dumps differ markedly between Mutshatsha and Lubudi territories, revealing the coexistence of distinct spatial regimes. In Mutshatsha territory, the increase in the Largest Patch Index combined with declining nearest-neighbour distances indicates spatial polarization around dominant mining complexes [77]. The high morphological intensification index suggests that growth is primarily driven by the expansion of existing dumps rather than by the creation of new disposal sites. Comparable configurations have been documented in the Solwezi region of Zambia, where large industrial mining complexes generate consolidated waste infrastructures [78]. Such spatial structures are typical of mining districts strongly integrated into export infrastructures, where economies of scale and logistical concentration shape the organization of production and waste management [79].

In contrast, Lubudi territory exhibits a more diffuse spatial configuration. The increase in the number of waste-dump patches is more pronounced, while growth in the Largest Patch Index remains moderate. This lower morphological intensification index indicates expansion through the multiplication of new dumping sites rather than through the enlargement of dominant deposits. Similar spatial patterns have been documented in several West African mining districts where industrial and artisanal activities coexist, producing a heterogeneous mosaic of intermediate-sized waste deposits [80]. Although artisanal mining rarely generates large dumps, which are typically associated with industrial processing chains, informal activities frequently occur on or around existing waste deposits. Such practices may fragment dump surfaces and increase the local dispersion of materials, as documented in Ghana [81].

The increase in morphological complexity observed in several deposits—particularly in Mutshatsha territory—further reflects the intensification of mining activities. Higher shape index and fractal dimension values indicate more irregular geometries and longer interfaces between dumps and the surrounding landscape matrix. In miombo ecosystems, the expansion of these interfaces can amplify ecological disturbances [31], while increased edge density exposes larger surfaces to erosion by wind and rainfall [82]. Local disturbances associated with artisanal reworking may further

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destabilize dump surfaces and facilitate the dispersion of fine particles toward adjacent agricultural areas [83]. Similar processes have been documented across southern African mining landscapes, where erosion remains difficult to eliminate but can be mitigated through improved geotechnical stabilization [84].

Taken together, the observed patterns—significant surface expansion, spatial polarization in Mutshatsha territory, relative diffusion in Lubudi territory, and increasing morphological complexity—are consistent with trajectories documented in mining regions integrated into international logistical corridors [85]. However, the coexistence of contrasting spatial regimes within a single Province indicates that integration into infrastructures such as the Lobito Corridor does not produce uniform morphological outcomes [86]. Instead, global material flows are translated locally through heterogeneous spatial configurations shaped by land-tenure legacies, industrial investment strategies, and interactions with artisanal mining [87]. The mine-waste-dump landscape of Lualaba therefore constitutes a material archive of more than a century of extractive intensification, continuously reconfigured by institutional transformations and increasingly shaped by integration into global mineral value chains [31,88].

The temporal evolution of dumps further reveals distinct phases of expansion. Between 2009 and 2015, the simultaneous increase in total surface area and the emergence of new dumps corresponds to the post-financial-crisis recovery of the Copperbelt, marked by renewed inflows of foreign capital. Between 2015 and 2020, growth trajectories diverge: in some territories expansion occurs mainly through enlargement of existing dumps, whereas in others the increase in patch numbers indicates the opening of new disposal sites [88]. This period coincides with the administrative reorganization that created Lualaba Province and with renewed productive intensification [31]. After 2020, continued expansion occurs in the context of rapidly rising global demand for copper and cobalt associated with the energy transition [89]. The coexistence of consolidation in some areas and spatial diffusion in others reflects differentiated local responses to these global market dynamics, consistent with patterns observed across mining regions in sub-Saharan Africa and Latin America [90,91].

Localized reductions in the surface area of certain dumps should not be interpreted as evidence of declining mining activity. In industrial mining systems, variations in dump extent frequently reflect the reorganization of waste-management infrastructures rather than reductions in material throughput. Such reductions may result from intra-site restructuring, when former dumping areas are reshaped or repurposed for new infrastructures such as haul roads or processing facilities [92]. They may also reflect operational consolidation; whereby smaller dumps are progressively integrated into larger engineered storage facilities to improve geotechnical stability and reduce transport costs [84]. In other cases, material rehandling and reuse—such as backfilling exhausted pits or stabilizing slopes—may reduce the surface footprint of dumps without decreasing total waste volumes [93]. Vegetation colonization or partial rehabilitation may further obscure dump boundaries in remote-sensing analyses, particularly in tropical environments [5].

Finally, the proximity of mine waste dumps to transport infrastructures reflects broader principles governing the spatial organization of extractive landscapes. Roads and haul routes reduce the cost of transporting large volumes of overburden and waste rock, leading to the preferential location of dumps near accessible corridors [94]. Similar spatial configurations have been documented in the Zambian Copperbelt and the Peruvian Andes [75,76]. However, the weak statistical relationship observed between road distance and dump size indicates that accessibility alone does not determine the scale or characteristics of waste-storage infrastructures [94]. Instead, the spatial distribution of mining waste is primarily structured by the internal organization of mining complexes, particularly the proximity to extraction pits and processing facilities that concentrate material flows [5]. In this perspective, transport infrastructure functions mainly as a supporting logistical framework within mining clusters rather than as the principal determinant of waste-dump spatial configuration.

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4.3. Socio-Ecological Implications

The expansion and increasing morphological complexity of mine waste dumps have significant implications for socio-ecological systems in the Copperbelt. First, the enlargement and irregular geometry of dumps contribute to the fragmentation of miombo woodlands, ecosystems central to regional biodiversity and rural livelihoods [95]. Increasing edge density due to mining activities intensifies edge effects, producing microclimatic changes and higher tree mortality near forest margins [96–98], as well as greater wildfire propagation in degraded landscapes [99]. At the landscape scale, these processes hinder natural regeneration and destabilize forest biomass, accelerating matrix degradation [96]. Establishing forest buffer zones around mine waste dumps could mitigate these effects by reducing edge disturbances and limiting particulate transfer toward surrounding agricultural areas. Vegetation belts can function as biological barriers capable of capturing airborne particles while contributing to ecological restoration in degraded mining landscapes [100].

Second, the increasing morphological complexity of dumps—reflected in higher fractal dimensions and interface density—expands surfaces exposed to atmospheric agents. In the sub-humid tropical climate of Lualaba, characterized by a pronounced dry season, unstabilized dumps may become important sources of dust emissions and trace-metal dispersion [101]. Studies in other copper mining basins show that particles derived from waste rock can be transported toward agricultural and residential areas [102]. In Lualaba, the growing interfaces between dumps, farmland, and settlements increase exposure to wind and water erosion [103], creating conditions conducive to diffuse contamination of surrounding socio-ecological systems [104].

Third, the lateral expansion of mine waste dumps intensifies land pressure and reinforces interactions between mining infrastructures and agropastoral systems [105]. The reduction of cultivable land and increasing proximity between dumps and farmland may affect soil fertility, crop productivity, and livestock health. Similar dynamics have been documented in the Zambian Copperbelt, where mining infrastructures overlap with agricultural landscapes and generate cumulative pressures on rural livelihoods [106]. In Lualaba, these processes contribute to increasing socio-ecological vulnerability in areas where extractive infrastructures and rural land uses intersect.

These dynamics highlight the need to integrate ecological restoration into extractive landscape management. Phytostabilization and progressive revegetation using native species tolerant to nutrient-poor substrates represent effective approaches to reduce erosion, dust emissions, and ecological degradation [107]. In the Zambian Copperbelt, indigenous species from families such as Fabaceae and Combretaceae show strong adaptation to contaminated substrates and contribute to the immobilization of metals such as copper and zinc [108]. Organic amendments, including compost or biochar, can further improve soil structure, support plant establishment, and enhance metal immobilization through soil–microbial interactions [109].

Technological innovations also offer new perspectives for monitoring restoration processes. Drone-based surveys enable high-resolution monitoring of dump morphology, slope instabilities, and erosion patterns [110]. Digital surface models help identify priority areas for stabilization and revegetation, while multispectral sensors can detect vegetation stress on restored sites [111]. However, the effectiveness of such approaches depends strongly on community participation. Participatory monitoring initiatives show that involving residents in environmental measurements improves transparency and strengthens environmental governance in mining regions [112].

Finally, integrating mine waste dumps into territorial planning frameworks linked to the Lobito Corridor appears essential. Coordinated planning of extraction and post-mining rehabilitation can reduce land disturbance, accelerate ecological restoration, and improve land-use efficiency [113]. In this perspective, spatially explicit analyses of land-use trajectories derived from remote sensing and land-cover transition assessment provide a robust framework for identifying dominant processes of landscape transformation and degradation, thereby supporting evidence-based territorial planning and environmental management [114]. The identification of spatial concentration patterns and

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morphological complexity therefore provides practical guidance for prioritizing remediation strategies adapted to different territorial contexts.

5. Conclusions

This study investigated the morpho-spatial dynamics of mine waste dumps in Lualaba Province by comparing the trajectories of Mutshatsha and Lubudi territories between 2009 and 2025. The results show that extractive intensification is expressed not only through the expansion of artificialized surfaces but also through a progressive reconfiguration of mining landscapes. Over the study period, the total area of mine waste dumps increased from approximately 1,900 ha to more than 6,400 ha, reflecting a substantial rise in mining waste accumulation associated with intensified extraction activities. Temporally, this evolution reveals a transition from a phase characterized by the proliferation of new dumps between 2015 and 2020 to a more recent phase dominated by the expansion and consolidation of existing deposits after 2020. Territorial analysis highlights contrasting spatial regimes. In Mutshatsha territory, growth is primarily driven by the enlargement of large dumps concentrated around active mining hubs, indicating increasing spatial consolidation of waste deposits. In contrast, Lubudi territory exhibits a more heterogeneous dynamic, characterized by the emergence of smaller and more spatially dispersed dumps accompanied by stronger morphological variability. Although many dumps are located relatively close to road infrastructure, statistical analyses indicate that road proximity has only a limited influence on their size or emergence. This suggests that the spatial organization of mine waste dumps is primarily structured by the internal configuration of mining operations rather than by transport accessibility alone. Overall, these results highlight the value of morpho-spatial monitoring for understanding the transformation of mining landscapes. Such approaches can provide valuable spatial information to support environmental remediation planning and the prioritization of post-mining landscape restoration strategies in rapidly expanding extractive regions.

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