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A Spatio-Temporal Analysis of Illegal Waste Disposal Site Activities at National Strategic Area in Developing Country – Deli Serdang Regency, Indonesia

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ABSTRACT

Illegal waste disposal site (IWDS) have become a chronic and severe environmental issue worldwide. Monitoring of IWDS is a central environmental issue in both developed and developing countries. The main aim of this study is to analyze changes in the shape and size of the IWDS over a period of time and to evaluate problems related to IWDS activities. This study also aims to determine the spatial and temporal pattern distribution of IWDS activities based on land use by combining time-series analysis from 2021 to 2023 using historical satellite imagery and ArcGIS. The results show an increase in IWDS locations in Deli Serdang from 98 in 2021 to 112 in 2022 and 120 in 2023. The total area IWDS in Deli Serdang also rose from 115,138.1971 m^2 in 2021 to 164,194.87 m^2 in 2023. Plantation/estate areas consistently recorded the highest number of IWDS incidents each year. The result shows that the trend highlights the tendency for IWDS to occur in natural vegetation-rich environments, which effectively hides these activities and complicates detection and access efforts.

Keywords: illegal dumping, spatio-temporal, time series, national strategic area, developing country.

INTRODUCTION

The illegal waste disposal sites (IWDS) present a significant and multifaceted challenge for countries worldwide (D'Amato and Zoli, 2012; Niyobuhungiro and Schenck, 2022; Ruffell and Dawson, 2009). This pervasive issue not only poses threats to environmental integrity but also imposes substantial financial burdens on governments (Agya et al., 2024; Matsumoto and Takeuchi, 2011; Yang et al., 2019). The costs associated with detecting and mitigating IWDS are considerable, encompassing expenses for surveillance, cleanup operations, and the implementation of preventive programs (Kubasek and Hrebicek, 2013; Matsumoto and Takeuchi, 2011; Youme et al., 2021). In Indonesia, as in many other nations, IWDS takes various forms, ranging from unauthorized dumping to improper handling of hazardous materials (Fariz et al., 2024; Ramadan et al., 2022). These activities not only degrade natural habitats and contaminate water sources but also hinder progress towards sustainable development goals and environmental conservation efforts. IWDS represents a pressing environmental and public health issue globally (Mazza et al., 2015; Triassi et al., 2015), driven by economic incentives to avoid waste disposal costs (Dlamini et al., 2017; Jordá-Borrell et al., 2014; Quesada-Ruiz et al., 2019). This illicit practice has been on the rise alongside increasing waste volumes, facilitated by its covert nature which often evades initial detection efforts (Du et al., 2023; Joo and Kwon, 2015; Yang et al., 2019). The long-term accumulation of IWDS not only threatens local economies and ecosystems but also poses significant health risks. Studies have shown that people living around IWDS are more likely to develop cancer (Aluko et al., 2022;

Mazza et al., 2015; Triassi et al., 2015). Detection of IWDS is a central environmental issue in both developed and developing countries (Glanville and Chang, 2015a; Massarelli, 2018; Yan et al., 2014). Monitoring IWDS is a highly complex task (Ichinose and Yamamoto, 2011; Karimi and Ng, 2022; Torres and Fraternali, 2021). Initially, due to its clandestine nature, perpetrators of IWDS actively seek to conceal their activities, making detection challenging for stationary monitoring facilities. This difficulty is particularly pronounced in sparsely populated regions (Biotto et al., 2009; Silvestri and Omri, 2008) like Deli Serdang, where IWDS incidents may go unnoticed for extended periods. Furthermore, the dynamics of IWDS locations and opportunities fluctuate over time, necessitating continuous advancements in detection capabilities (Biotto et al., 2009; Hidalgo et al., 2019). This dynamic nature further complicates regulatory efforts aimed at timely identifying and addressing IWDS activities.

Geospatial and remote sensing (RS) technologies have experienced extraordinary development, becoming increasingly accessible and integral to everyday life. When combined with Geographic Information Systems (GIS), these technologies play crucial roles across multiple stages of Municipal Solid Waste Management (MSWM) (Glanville and Chang, 2015b; Karimi and Ng, 2022). They are employed in tasks such as optimizing waste collection routes, assessing dumping site's size and capacity, and detecting and monitoring landfill fires.

RS technologies contribute by providing real-time or near-real-time data on waste accumulation, site conditions, and environmental impacts (Glanville and Chang, 2015b; Silvestri and Omri, 2008; Yan et al., 2014). Satellite imagery and aerial surveys enable precise mapping and analysis, facilitating proactive management strategies to mitigate environmental risks associated with waste disposal (Dabholkar et al., 2017; Di Fiore et al., 2017; Du et al., 2021). GIS enhances these capabilities by integrating spatial data to optimize logistical operations, improve efficiency in waste transportation, and support decision-making processes for sustainable waste management practices(Seror and Portnov, 2018; Sodoke et al., 2022; Tasaki et al., 2007).

Simple essential tools and applications such as Google Maps, Bing Maps, Google Earth, and Google Earth Pro are valuable resources for climate and environmental research, leveraging their access to high-resolution satellite imagery. Google Earth Pro, a virtual globe software, amalgamates a comprehensive array of remotely sensed and modelled images from diverse satellite and aircraft datasets captured at various intervals. Within Google Earth Pro, users can zoom in to resolutions ranging from 1 to 15 meters per pixel, facilitating the identification and examination of geographic features like river basins, canyons, agricultural landscapes, mountains, and their corresponding elevations. Google Earth Pro is a highly effective tool for generating data in regions lacking high-quality RS data. It facilitates the identification of IWDS within urban areas and surrounding regions, offering insights into the changing patterns of IWDS activities over time.

The objective of this study was to analyze changes in the shape and size of the IWDS over a period of time and to evaluate problems related to IWDS activities. This study also aims to determine the spatial and temporal pattern distribution of IWDS activities based on land use.

METHODOLOGY

This study was conducted in Deli Serdang Regency, recognized as one of Indonesia's National Strategic Areas under Presidential Regulation 62/2011. Located along the eastern coast of Sumatra, Deli Serdang spans from approximately 2°57' North Latitude to 3°16' North Latitude and 98°33' East Longitude to 99°27' East Longitude, covering an area of about 2,497.72 square kilometers or 249,772 hectares. The regency is comprised of 22 districts and 394 villages. Figure 1 depicts the map of Deli Serdang Regency. According to data from the Deli Serdang Central Bureau of Statistics, the population in 2023 was 1,941,374 individuals, with 983,675 men and 970,311 women in the area. This population is distributed across 453,533 households, averaging approximately four individuals per household.

The study area faces significant waste management challenges, with Deli Serdang generating an estimated 1.097 tons of waste per day or approximately 400,716 tons annually (Fariz et al., 2023). Of this total waste generation, only 62.72% is effectively managed by formal waste management systems, leaving approximately 37.28% unmanaged (Fariz et al., 2023). This unmanaged waste presents a potential for the emergence of IWDS activities. To analyze the dynamics of IWDS pattern from 2021 to 2023, a time-series

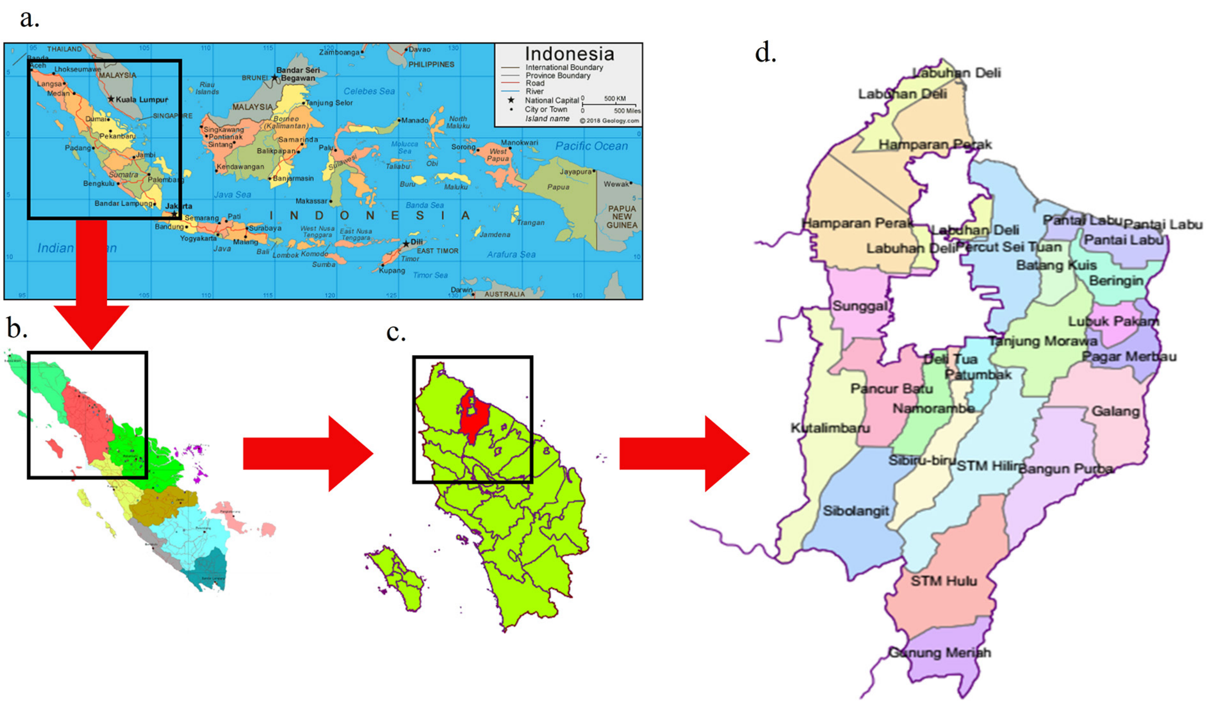

Figure 1. The map of study area: (a) Indonesia, (b) Sumatera Island, (c) North Sumatera, (d) Deli Serdang Regency

approach was employed, comparing satellite images of identified IWDS locations at different intervals. Historical satellite images were accessed and analyzed using the historical imagery feature in Google Earth Pro software (version 7.3.6.9796 (64-bit)). A total of 124 IWDS were selected for detailed study based on their prevalence and accessibility within Deli Serdang Regency.

Using ArcGIS 10.8 software, polygons were drawn around each IWDS to calculate both the area and perimeter of these sites. The area measurement was prioritized over perimeter due to the irregular shapes and fragmented nature of IWDS, providing a more accurate estimate of their size and spatial impact. This method facilitated a comprehensive time-based comparison of IWDS, allowing researchers to track changes in site extent and distribution over the study period.

RESULTS AND DISCUSSION

IWDS distribution pattern

From a time-series analysis at the same IWD location spanning from 2021 to 2023 across 124 locations, it has been observed that there is a notable increase in the number of IWDS in Deli Serdang. As Shown in Table 1, the data reveals that in 2021 there were 98 IWDS locations in Deli Serdang, which increased to 112 in 2022 and 120 in 2023. This consistent rise indicates a clear upward trend in the prevalence of IWDS in the region over the three years. The results show a comprehensive overview of the prevalence of IWDS across various districts from 2021 to 2023 (Fig. 2). The study shows that the proliferation of IWDS in Deli Serdang from 2021 to 2023 underscores a pressing environmental challenge. Each year, the number of identified IWDS has steadily increased, reflecting not only the persistence of illegal dumping but also the evolving landscape of waste management issues in the region.

This study also shows that there is a fluctuating increase in the area of IWDS in Deli Serdang as shown in (Table 2). The data from Table 2 illustrates a fluctuating increase in the area occupied by IWDS across various districts in Deli Serdang from 2021 to 2023. Each district shows changes in the total area of IWDS over the three-year period. In 2021, notable areas of IWDS were identified in several districts, with significant figures such as Hamparan Perak occupying 18,505.16 m^2, Percut Sei Tuan with 32,007.06 m^2, and Sunggal with 22,661.66 m^2. By 2022, there was a general increase in the area of IWDS across most districts. Notably, Percut Sei Tuan saw a substantial rise to 56,639.70 m^2, reflecting a significant expansion

Table 1. IWDS distribution from 2021 to 2023

District	2021	2022	2023
Biru-Biru	0	0	1
Delitua	2	2	2
Hamparan Perak	4	4	4
Labuhan Deli	12	12	12
Namorambe	1	1	1
Pagar Merbau	0	0	1
Pancur Batu	6	7	7
Patumbak	9	10	10
Percut Sei Tuan	43	51	56
Senembahtanjungmuda Hilir	1	2	2
Sunggal	9	9	10
Tanjung Morawa	11	14	14
Total	98	112	120

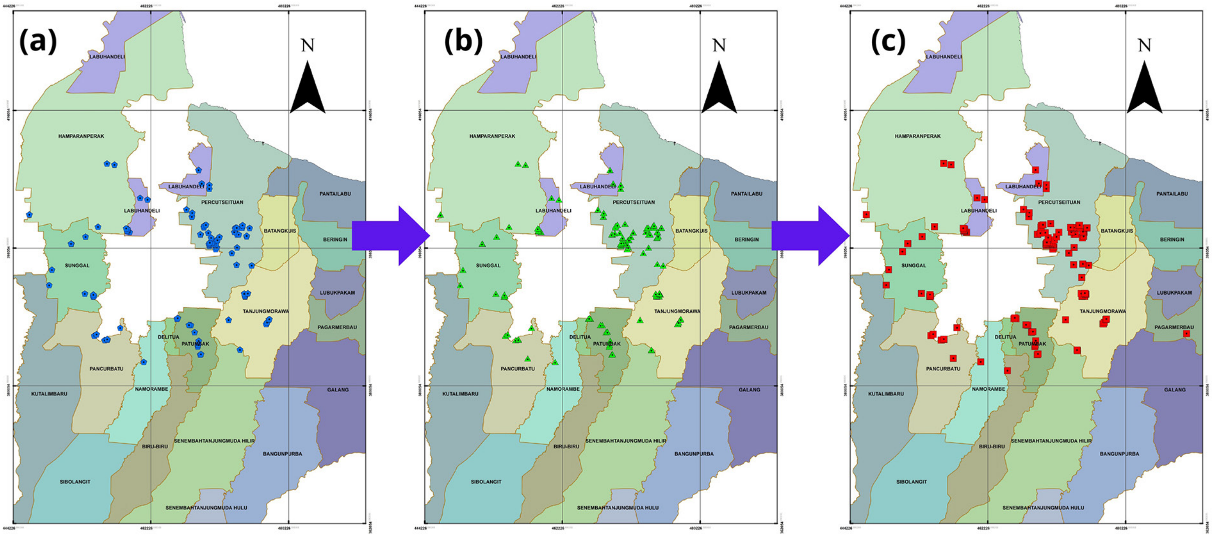

Figure 2. IWDS temporal pattern across various districts in Deli Serdang (a) 2021 (b) 2022 (c) 2023

Table 2. IWDS area in each district (m^2)

District	2021	2022	2023
Biru-Biru	-	-	820.86
Delitua	2,778.03	2,830.45	3,639.37
Hamparanperak	18,505.16	23,676.95	25,372.49
Labuhandeli	6,303.76	7,481.88	7,164.31
Namorambe	944.49	3,095.81	2,858.81
Pagarmerbau	-	-	166.06
Pancurbatu	10,043.21	17,953.40	13,898.40
Patumbak	8,482.86	9,602.18	11,705.04
Percutseituan	32,007.06	56,639.70	55,896.52
Senembahtanjungmuda Hilir	1,229.43	1,333.40	1,309.80
Sunggal	22,661.66	23,124.25	25,028.35
Tanjungmorawa	12,182.54	21,878.13	16,334.85
Total	115,138.197	167,616.147	164,194.87

of illegal dumping activities in that area. Similarly, districts like Sunggal and Tanjung Morawa also experienced considerable increases in IWDS areas In 2023, while the total IWDS area slightly decreased compared to 2022, many districts maintained substantial areas dedicated to IWDS activities. Percut Sei Tuan, for instance, still reported a significant IWDS area of 55,896.52 m^2. Other districts like Hamparan Perak and Sunggal also retained large IWDS areas, demonstrating persistent environmental challenges despite fluctuations in total area across different districts in Deli Serdang.

From 2021 to 2023, Percut Sei Tuan consistently became the most significant area for IWDS in Deli Serdang. In 2021, the IWDS area in Percut Sei Tuan was recorded at 32,007.06 m^2. This area substantially increased in 2022, reaching 56,639.70 m^2, indicating a significant escalation in illegal dumping activities. By 2023, although there was a slight decrease, the IWDS area remained substantial at 55,896.52 m^2. Concurrently, IWDS locations increased from 43 in 2021, 51 in 2022 to 56 in 2023 (Fig. 3), underlining the persistent and growing issue of illegal waste disposal in Percut

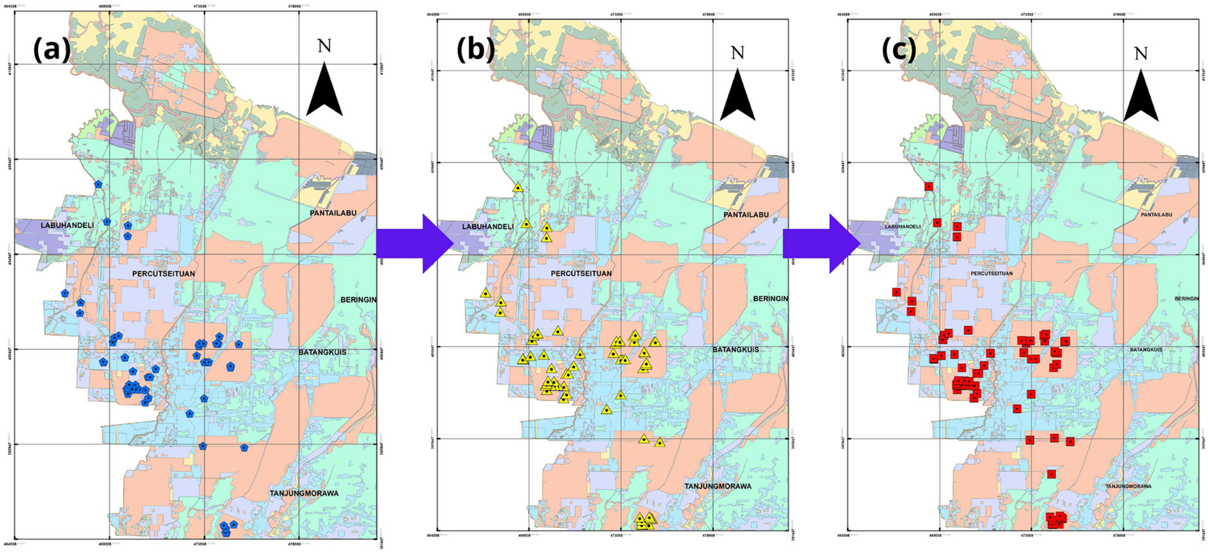

Figure 3. IWDS trends in Percut Sei Tuan District (a) 2021 (b) 2022 (c) 2023

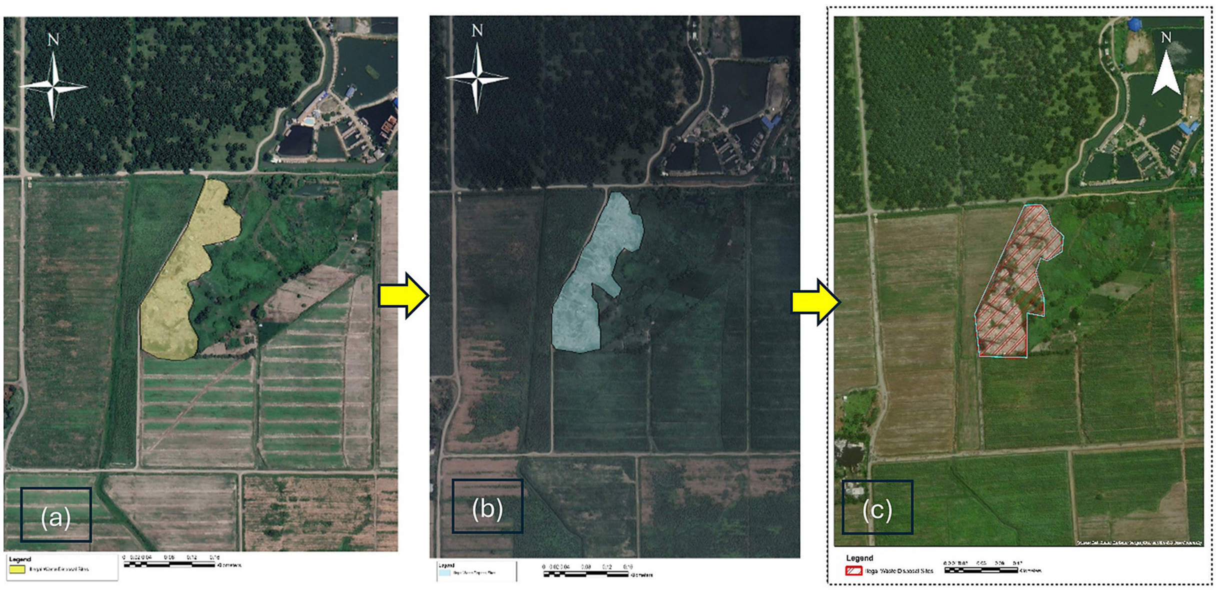

Figure 4. The largest IWDS location (a) 2021 (b) 2022 (c) 2023

Sei Tuan. This data underscore Percut Sei Tuan as a focal point for illegal waste disposal in the Deli Serdang. The largest IWDS location identified in Deli Serdang was in Hamparan Perak (Fig. 4), which exhibited substantial growth over the years. In 2021, the IWDS measured 14,566.53 m^2. These IWDS activities expanded to 16,713.04 m^2 in 2022 and increased to 19,296.20 m^2 by 2023.

Figure 5 shows the comparative trends in IWDS areas across various locations from 2021 to 2023. Examining the progression of IWDS trends using time-series analysis over the past three years provides valuable insights into environmental sustainability and regulatory compliance. Figure 6 presents data from 2021 to 2023, outlining fluctuations and patterns in IWDS activities. These figures highlight a concerning rise in IWDS activities. Understanding these dynamics is crucial for authorities to identify hotspots, assess the effectiveness of interventions, and propose evidence-based solutions to combat IWDS activities.

IWDS distribution based on land use

This study shows that IWDS in Deli Serdang are categorized across five distinct land use types. Understanding the spatial and temporal patterns of IWDS activity within these land use categories is crucial for effective management and mitigation strategies (Khumalo et al., 2021; Kim et al., 2008; Muindi et al., 2022). Authorities can identify high-risk areas and trends over time by

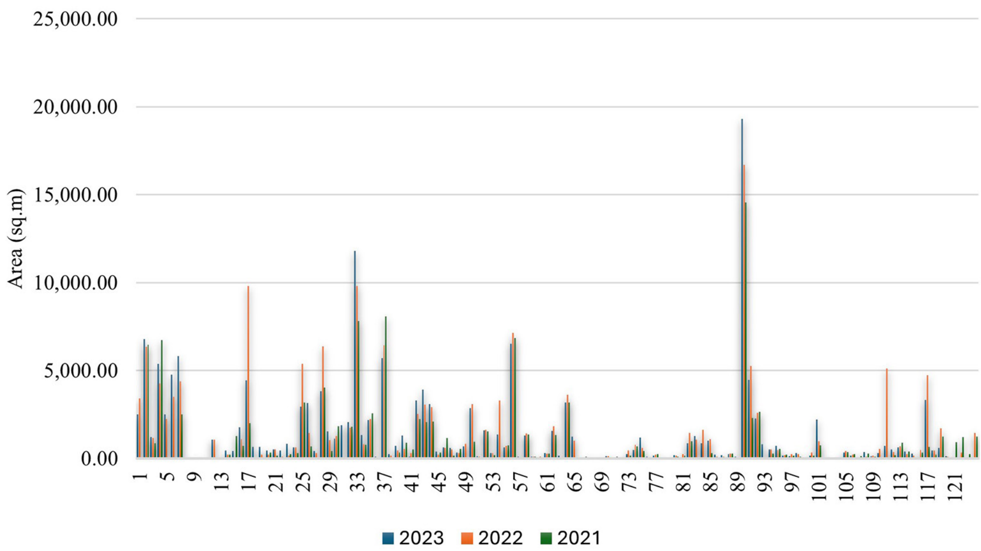

Figure 5. The comparative trends of IWDS area

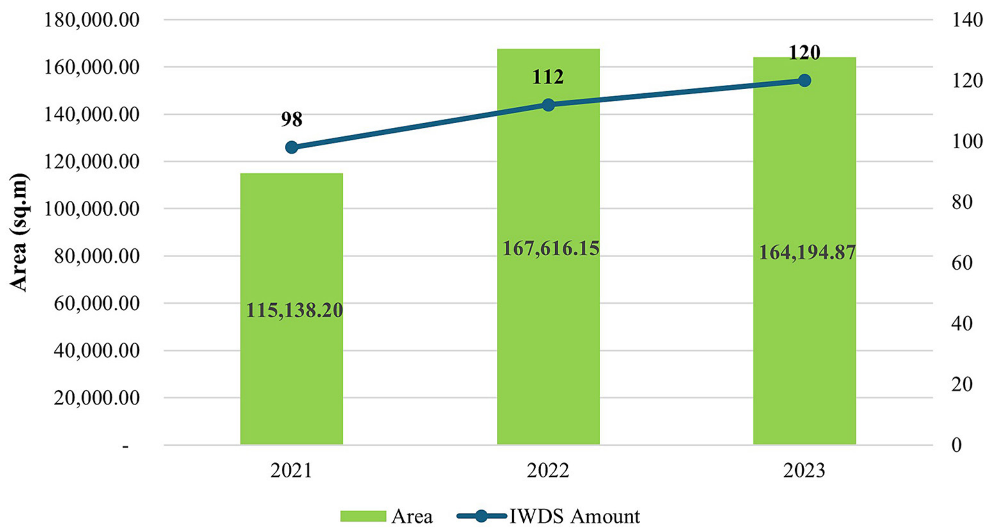

Figure 6. The IWDS trends from 2021 to 2023

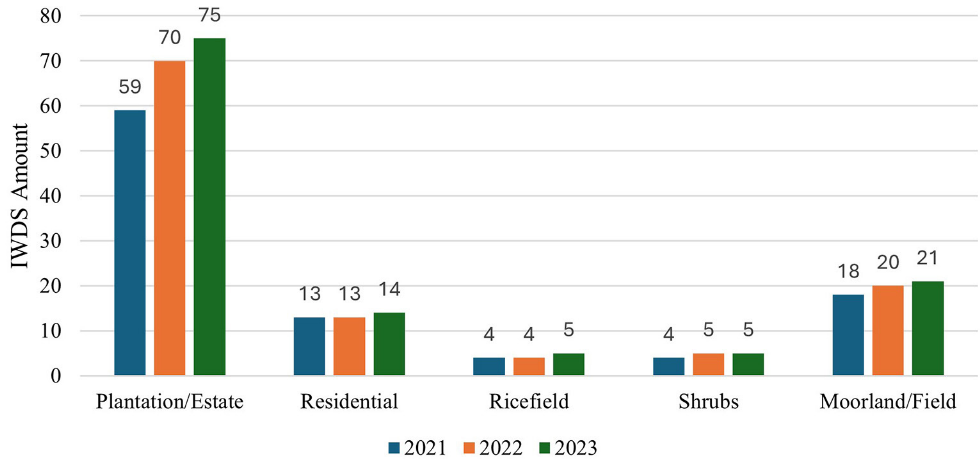

Figure 7. IWDS distribution based on land use

analyzing how IWDS are distributed across different land uses. This data enables the implementation of targeted preventive measures tailored to each land use category, such as enhanced monitoring, stricter enforcement of regulations, and community engagement initiatives.

Figure 7 provides a comprehensive overview of IWDS across various land use categories in Deli Serdang from 2021 to 2023. Plantation/estate areas consistently recorded the highest number of IWDS incidents each year. This pattern is primarily due to the secluded and often remote nature of IWDS locations (D'Amato et al., 2018; Nagpure, 2019; Tasaki et al., 2007), making plantations ideal locations for illegal waste dumping. The covert nature of IWDS activities aligns with their tendency to occur in hidden or less accessible areas, which complicates detection by authorities. As a result, plantation/estate emerge as prominent sites for illegal waste disposal, highlighting substantial challenges in effectively monitoring and enforcing waste management regulations in these environments characterized by dense vegetation and remote locations.

Residential areas, from 2021 to 2023 the presence of IWDS within residential areas exhibited a stable trend with minor fluctuations. In 2021, a total of 13 IWDS were identified within residential zones, a number that remained unchanged in 2022. By 2023, there was a slight increase, with 14 IWDS locations recorded. This result indicates a persistent but manageable issue of illegal waste dumping occurring within neighborhoods designated for housing. The relatively consistent number of IWDS incidents over the three-year period suggests ongoing challenges in waste management enforcement or consistent illegal dumping activities within these residential environments. In rice fields, there was a gradual increase in IWDS incidents from 4 in 2021 to 5 in 2023. Similar patterns were observed in shrublands, where IWDS incidents increased from 4 in 2021 to 5 in 2022 and 2023, reflecting ongoing challenges in managing waste in natural and semi-natural landscapes. Moorland/field areas have shown a noticeable increase in IWDS incidents, with numbers rising from 18 in 2021 to 21 in 2023. This trend highlights the tendency for IWDS to occur in natural environments rich in vegetation, which effectively hides these activities, thereby complicating detection and access efforts. Moreover, the clandestine nature of IWDS contributes to a lack of public awareness regarding these illegal activities, known only to

Table 3. The IWDS area based on land use

Land use category	2021 IWDS amount	2021 IWDS area (m^2)	2022 IWDS amount	2022 IWDS area (m^2)	2023 IWDS amount	2023 IWDS area (m^2)
Plantation/Estate	59	99,858.88	70	148,248.21	75	141,527.84
Residential	13	4,109.25	13	3,400.86	14	4,630.97
Ricefield	4	2,521.81	4	2,641.14	5	4,313.94
Shrubs	4	1,461.85	5	1,273.01	5	1,384.62
Moorland/Field	18	7,466.07	20	12,325.44	21	12,637.16

Table 4. IWDS distribution based on land use from 2021 to 2023

IWDS	2021 (m^2)	2022 (m^2)	2023 (m^2)	Land use	IWDS	2021 (m^2)	2022 (m^2)	2023 (m^2)	Land use
1	-	3,422.64	2,509.08	Moorland/Field	25	3,173.51	5,370.25	2,960.89	Plantation/Estate
2	6,471.21	6,363.96	6,778.10	Plantation/Estate	26	701.53	1,458.54	3,158.90	Plantation/Estate
3	873.37	1,157.87	1,227.26	Plantation/Estate	27	-	298.10	426.02	Plantation/Estate
4	6,720.65	4,282.22	5,377.80	Plantation/Estate	28	4,031.11	6,387.76	3,817.24	Plantation/Estate
5	-	2,235.95	2,516.62	Plantation/Estate	29	424.67	1,041.17	1,539.83	Plantation/Estate
6	-	3,496.48	4,779.40	Plantation/Estate	30	1,844.54	1,282.80	1,143.40	Plantation/Estate
7	2,506.30	4,370.42	5,831.67	Plantation/Estate	31	-	-	1,899.41	Ricefield
8	-	-	82.85	Plantation/Estate	32	1,818.17	1,744.74	2,079.04	Plantation/Estate
9	38.71	72.36	20.40	Plantation/Estate	33	7,820.30	9,804.96	11,792.81	Plantation/Estate
10	-	63.21	70.93	Plantation/Estate	34	783.95	805.84	1,333.90	Plantation/Estate
11	-	-	47.49	Plantation/Estate	35	2,561.69	2,238.41	2,187.41	Plantation/Estate
12	-	1,073.39	1,083.91	Plantation/Estate	36	-	-	98.95	Moorland/Field
13	-	38.45	30.83	Shrubs	37	8,073.59	6,429.78	5,718.60	Plantation/Estate
14	235.60	215.75	468.06	Moorland/Field	38	-	175.68	237.23	Plantation/Estate
15	1,274.55	-	430.40	Residential	39	339.54	444.16	720.83	Plantation/Estate
16	732.09	1,086.35	1,783.14	Residential	40	907.82	532.20	1,294.94	Ricefield
17	2,017.16	9,804.05	4,441.27	Plantation/Estate	41	503.67	294.57	104.85	Plantation/Estate
18	-	-	650.04	Plantation/Estate	42	2,245.80	2,533.39	3,307.61	Plantation/Estate
19	83.39	213.35	675.16	Plantation/Estate	43	2,062.94	3,069.00	3,904.19	Plantation/Estate
20	326.35	224.93	466.67	Plantation/Estate	44	2,088.15	2,907.33	3,104.42	Moorland/Field
21	159.27	507.31	507.73	Plantation/Estate	45	329.15	232.45	399.97	Plantation/Estate
22	38.98	99.77	468.07	Moorland/Field	46	1,147.92	610.79	637.92	Plantation/Estate
23	249.92	174.35	834.43	Moorland/Field	47	166.36	510.22	597.17	Plantation/Estate
24	323.81	636.17	634.72	Moorland/Field	48	532.23	297.06	331.76	Residential
49	-	825.77	703.52	Plantation/Estate	73	161.43	467.50	254.60	Plantation/Estate
50	944.49	3,095.81	2,858.81	Plantation/Estate	74	680.69	778.66	472.79	Plantation/Estate
51	49.95	105.49	131.51	Plantation/Estate	75	416.31	599.48	1,203.40	Plantation/Estate
52	1,528.67	1,623.97	1,599.62	Plantation/Estate	76	12.05	36.16	94.29	Moorland/Field
53	204.79	318.82	308.53	Plantation/Estate	77	236.26	213.86	160.06	Moorland/Field
54	-	3,312.68	1,378.74	Plantation/Estate	78	79.20	57.32	46.80	Moorland/Field
55	749.88	708.60	644.57	Plantation/Estate	79	-	45.59	41.62	Moorland/Field
56	6,854.30	7,144.69	6,511.88	Plantation/Estate	80	91.97	164.79	197.26	Plantation/Estate
57	76.23	53.74	95.51	Plantation/Estate	81	166.51	242.67	87.84	Plantation/Estate
58	1,360.48	1,416.00	1,309.33	Plantation/Estate	82	981.30	1,463.75	853.28	Plantation/Estate
59	90.07	109.62	96.00	Residential	83	-	1,083.41	1,291.02	Plantation/Estate
60	88.04	109.33	47.51	Shrubs	84	-	1,632.50	859.16	Plantation/Estate
61	279.67	272.51	299.01	Ricefield	85	305.06	1,087.31	1,008.98	Plantation/Estate
62	1,349.62	1,827.82	1,578.61	Plantation/Estate	86	74.34	117.86	224.87	Ricefield
63	-	-	166.06	Plantation/Estate	87	64.26	110.46	193.67	Residential
64	3,189.30	3,622.13	3,189.64	Plantation/Estate	88	286.43	281.49	247.16	Plantation/Estate
65	-	1,005.42	1,258.99	Plantation/Estate	89	43.92	88.08	101.63	Moorland/Field
66	-	-	50.81	Plantation/Estate	90	14,566.53	16,713.04	19,296.20	Plantation/Estate
67	81.28	78.12	115.62	Plantation/Estate	91	2,298.48	5,275.40	4,467.95	Plantation/Estate
68	44.41	62.36	31.71	Moorland/Field	92	2,645.62	2,590.40	2,259.81	Moorland/Field
69	-	80.67	66.61	Residential	93	-	-	820.86	Plantation/Estate
70	72.88	133.50	123.28	Residential	94	269.24	518.77	509.65	Residential
71	93.77	51.99	38.80	Moorland/Field	95	533.60	481.76	721.18	Residential
72	-	-	59.51	Plantation/Estate	96	219.61	189.55	149.41	Residential

Cont. Table 4.

97	154.36	252.82	138.46	Residential	111	-	5,112.10	732.88	Plantation/Estate
98	95.56	243.96	296.04	Plantation/Estate	112	179.99	356.33	511.90	Moorland/Field
99	83.72	71.01	53.49	Residential	113	882.68	684.37	617.42	Shrubs
100	170.76	334.52	161.32	Plantation/Estate	114	402.52	264.64	411.29	Shrubs
101	761.54	985.37	2,213.22	Plantation/Estate	115	88.61	176.22	277.56	Shrubs
102	59.79	48.08	44.62	Moorland/Field	116	337.18	484.62	60.09	Moorland/Field
103	49.98	47.07	21.41	Residential	117	655.63	4,739.16	3,323.55	Plantation/Estate
104	32.65	22.21	12.51	Residential	118	234.44	454.38	456.42	Moorland/Field
105	355.45	440.77	351.01	Plantation/Estate	119	1,259.98	1,718.57	595.70	Ricefield
106	257.71	230.54	151.22	Plantation/Estate	120	85.23	96.31	136.06	Plantation/Estate
107	134.60	61.08	67.87	Plantation/Estate	121	937.32	-	-	Plantation/Estate
108	283.30	107.75	372.65	Moorland/Field	122	1,229.43	327.98	-	Plantation/Estate
109	100.42	151.28	127.71	Plantation/Estate	123	263.39	-	-	Plantation/Estate
110	-	558.07	320.06	Plantation/Estate	124	1,243.34	1,439.89	-	Plantation/Estate

a limited number of individuals engaged in such practices. This covert behavior further obstructs efforts to address and mitigate the environmental and social consequences associated with IWDS in Deli Serdang. Table 3 shows the IWDS area distribution based on land use.

Table 4 shows the IWDS Distribution Based on Land Use from 2021 to 2023. In 2021, Plantation/Estate areas in Deli Serdang reported the highest incidents of IWDS, totaling 99,858.88m^2. This area shows a significant increase to 148,248.21 m^2 in 2022, indicating a substantial escalation in IWDS activities within these concealed and densely vegetated environments. By 2023, although there was a slight decrease, the area remained considerable at 141,527.84 m^2, underscoring the persistent nature of IWDS in plantation/estate settings despite efforts to mitigate such activities.

Residential areas have shown a fluctuating trend in illegal waste disposal sites (IWDS) incidents from 2021 to 2023. Initially starting at 4,109.25 m^2 in 2021, the affected area decreased to 3,400.86 m^2 in 2022, before increasing to 4,630.97 m^2 in 2023. This variability indicates ongoing challenges in managing waste disposal within residential zones. Factors contributing to these fluctuations could include changes in population density, urban development activities, and shifts in waste management policies or practices. The rise in 2023 highlights a potential escalation in IWDS activities, possibly due to increased urbanization pressures or inadequate waste management infrastructure.

Ricefield areas witnessed fluctuating IWDS incidents from 2,521.81 m^2 in 2021 to 2,641.14 m^2 in 2022, before experiencing a notable increase to 4,313.94 m^2 in 2023. This variability indicates potential challenges in monitoring and regulating waste disposal in agricultural landscapes, influenced by seasonal agricultural practices and accessibility.

Shrubs areas maintained relatively stable IWDS occurrences across the years, ranging from 1,461.85 m^2 in 2021 to 1,384.62 m^2 in 2023. The consistent nature of these incidents highlights the persistent challenge of detecting and addressing illegal dumping activities in shrub-covered environments, where the dense vegetation provides ample cover for illegal practices.

Moorland/Field areas exhibited a consistent upward trend in IWDS incidents, increasing from 7,466.07 m^2 in 2021 to 12,325.44 m^2 in 2022 and further to 12,637.16 m^2 in 2023. This pattern underscores the propensity for IWDS to occur in natural and less accessible terrains, characterized by dense vegetation that complicates both detection and mitigation efforts.

Illegal waste disposal sites are strategically positioned in remote and obscure locations, intentionally hidden from casual observation and regulatory oversight (Faria et al., 2023; Jordá-Borrell et al., 2014; Seror and Portnov, 2018). These sites are often situated away from main roads and urban centers, making them challenging for authorities and environmental agencies to detect and monitor effectively (Glanville and Chang, 2015a; Matos et al., 2012; Tasaki et al., 2007). The deliberate choice of such secluded areas underscores the clandestine nature of illegal waste disposal operations, which evade legal scrutiny and environmental regulations. This poses significant environmental and public health risks, as unregulated waste disposal can lead to soil contamination, groundwater pollution, and air quality deterioration (Carriero et al., 2018; Triassi et al., 2015; Vaverková et al., 2019). Addressing these challenges requires robust enforcement measures, enhanced surveillance technologies, and community engagement to prevent and mitigate the adverse impacts of IWDS. Efforts to combat these practices must be multifaceted, integrating spatial analysis tools and collaborative strategies among stakeholders to ensure effective environmental stewardship and sustainable development

CONCLUSIONS

A spatio-temporal analysis of 124 IWDS in Deli Serdang Regency has been conducted using historical satellite images from Google Earth Pro software (version 7.3.6.9796) and combining with ArcGIS 10.6 software. This study employed spatio-temporal data to analyze IWDS locations across different time periods. The results indicate an increase in IWDS locations in Deli Serdang from 98 in 2021 to 112 in 2022 and 120 in 2023. Concurrently, the total area IWDS in Deli Serdang also rose from 115,138.1971 m^2 in 2021 to 164,194.87 m^2 in 2023. The study highlights plantation/estate areas as the most prevalent locations for IWDS in Deli Serdang, with a rise in the number of IWDS from 59 in 2021 to 70 in 2022 and 75 in 2023. Moorland/field areas also exhibited increased IWDS incidents, from 18 in 2021 to 20 in 2022 and 21 in 2023. This pattern underscores the characteristics of IWDS in Deli Serdang, which is situated in densely vegetated and difficult-to-access locations. These aid in concealing IWDS activities and complicating detection efforts by the authorities. The methodology employed in this study can be expanded to encompass entire cities or even multiple cities over specific time periods. Adopting technology-driven monitoring and detection systems for IWDS represents a crucial step forward for authorities worldwide. By harnessing the power of high satellite imagery, GIS, and advanced data analytics, authorities can significantly enhance their ability to detect, monitor, and mitigate IWDS activities promptly and efficiently.

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