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From Illegal Waste Dumps to Beneficial Resources Using Drone Technology and Advanced Data Analysis Tools: A Feasibility Study

Adi Mager and Vered Blass *

The Porter School of the Environment and Earth Sciences, Tel Aviv University, Tel Aviv 6997801, Israel
* Correspondence: vblass@tauex.tau.ac.il; Tel.: +972-73-380-4418

Abstract: In a resource-constrained world, there is ongoing concern over the exploitation and potential future shortage of Earth's natural resources. In this paper, we present the results of two pilot studies in which we used drone technology with spatial mapping tools and environmental and economic analysis to map illegal waste sites. Besides the technical feasibility, we aimed at understanding the benefits, costs, and tradeoffs of extracting the materials stocked therein, transforming illegal waste sites into valuable resources. The innovation of our work is reflected in the integration of existing technologies for aerial mapping and economic\environmental assessment methodologies for promoting a local circular economy. The pilot results suggest that it is feasible to identify valuable materials left on the ground in the form of unattended, illegally disposed waste. Our initial national estimates for the illegal waste cleanup based on the pilot results suggest that the treatment cost in Israel can be reduced by 58 million USD and even reach zero, with the potential to generate up to 82.8 million USD profits. Finally, we link our results to the Sustainable Development Goals framework and suggest how mapping and implementing the recycling potential can promote achieving some of the goals. Our work provides missing data that the state, local authorities, contractors, and companies that monitor and manage waste and recycled raw materials may find useful.

Keywords: illegal waste site; drone technology; data analysis; economic assessment; SDG

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1. Introduction

Globally, 2.01 billion tons of waste were generated in 2016, and it is projected that the amount will increase by 70 percent by 2050 to reach 3.40 billion tons. Every day, governments and individuals make waste management decisions that impact the health, productivity, and cleanliness of communities. Unmanaged waste contributes to air and water pollution, flooding, and transmitting diseases while harming animals that unknowingly consume waste and negatively affecting the economy [1].

According to the European Commission [2], construction is one of the most wasteful and polluting industries. The construction industry and the built environment as a whole generate approximately 40% of global greenhouse gas (GHG) emissions. In Europe, construction and demolition waste (CDW) accounts for approximately 60% of the total produced waste. Despite being a large and complex industry, construction rarely adopts a life-cycle approach toward the buildings and infrastructure it produces. The construction sector is characterized by complex and hierarchical supply chains that include large construction materials and heavy manufacturing processes. Consequently, construction and other aspects of the built environment have been underestimated in terms of their environmental impact. The main environmental impacts associated with open-air final disposal include air contamination, odors, greenhouse gas emissions, vectors of diseases, and the contamination of surface water and groundwater [3].

The main factors contributing to illegal CDW dumping include the lack of treatment facilities and the need to travel long distances to authorized landfills or recycling facilities.

Furthermore, some waste generators are unaware of their obligation to transport waste to authorized treatment facilities [4,5]. It has been observed that environmental law enforcement authorities often have limited financial and human resources [6,7]. Solid waste (SW) and CDW dumping are well-known environmental issues worldwide. Approximately 410 billion dollars are invested annually in the disposal and recycling of global waste [8].

It has traditionally been the goal of waste management to stabilize waste in situ or transport it to authorized landfills to limit potential air, water, and soil pollution and their negative environmental impacts. In this approach, the waste's untapped "resource" potential has been overlooked, as well as the possibility of transforming it into useful goods. The CDW stream has the potential for high recycling and reuse rates due to its significant amount of waste, large volume, and heterogeneous composition [9,10].

There is an increase in environmental contamination and disease spread in developing countries because of unsustainable waste management practices. A significant problem in the open dumping of waste in uncontrolled sites is the waste burning in open settings and the mismanagement of the leachate produced at the final disposal sites [11]. Uncontrolled disposal in open spaces near water bodies is a widespread problem, posing a public health risk. Many studies conducted in developing countries have suggested possible solutions for improving SW management. Among these are organic waste buyback programs with compost or biogas production [12], the implementation of waste-to-energy facilities and technologies [13], waste-to-energy combined with recycling [14], and the production of energy from biomass waste by briquette production [15]. However, many barriers remain to improving the formal collection, treatment, and disposal of wastes, and environmental contamination resulting from illegal dumping remains a major global issue [16]. Therefore, it is imperative to identify and implement solutions that consider appropriate SWM patterns for each context.

As part of the universal call to action to end poverty, protect the environment, and ensure that, by 2030, all people live peaceful and prosperous lives, the Sustainable Development Goals (SDG) were adopted by the United Nations in 2015 [17]. The construction industry plays a crucial role in achieving the SDG by developing sustainable infrastructure projects, particularly in developing countries. More than half of the SDGs explicitly or implicitly address waste management. One of the key goals in the context of this work is SDG 12: Responsible Consumption and Production. The achievement of Goal 12 depends upon a solution to the rapid expansion of global material consumption and the accompanying increase in material footprints per capita. It calls for urgent action necessary to curb the overuse of natural resources, implement policies and actions to reduce waste, improve resource efficiency, and incorporate sustainable practices into all sectors of the economy. SDG sub-targets 12.12, 12.4, and 12.5 are especially relevant to this study, providing sound management strategies for illegal dumpsites and engaging citizens, businesses, and stakeholders to move from linear to circular waste management methods. Achieving one SDG may affect others in synergistic or tradeoff modes. It has been suggested by Keesstra et al. (2016) that soil functions and ecosystem services are interconnected and have important links to several SDGs. The soil provides food and clean water, as well as biodiversity. Therefore, illegal waste dumps should be removed, and the affected areas should be reclaimed, rehabilitated, or restored in accordance with the SDGs to prevent further land degradation [18].

In 2050, close to 70% of the global population will reside in cities, according to the United Nations Global Compass (UNGC) [19]. Thus, cities play a key role in achieving a sustainable future for the planet. In line with International SDG 8, the construction industry promotes sustainable economic growth by providing decent work and economic growth for all. In particular, Target 8.4 is relevant to our work-"improve consumption and production of resources". Furthermore, SDG 11 emphasizes the central role urbanization plays in sustainable development, elucidating the need for cities and communities that are inclusive, safe, resilient, and sustainable. As we focus on reducing the environmental impacts of cities, Target 11.6 is particularly relevant to this study. In addition, the construction industry plays an important role in preserving the biodiversity (SDG 15); however, this is not usually a priority area. The construction industry adversely affects the environment through activities such as waste disposal from project sites, biodiversity loss, and the use of building materials. Furthermore, it is directly related to forests and targets biodiversity. Finally, the sound management of chemicals and wastes (SMCW) is a specific target under SDG 12 but is also a topic of discussion under SDG 3 on Good Health and Well-being and SDG 6 on Clean Water and Sanitation [17].

The COVID-19 pandemic added to the impending environmental crisis and highlighted the growing importance of promoting sustainability across the government, industry, and the public. It underscored the need for immediate action. Today's reality emphasizes the importance of digitalization for a resilient future. According to Sultan et al. [20], waste management data play a crucial role in creating local policies and plans. With more accurate data, governments can allocate resources more effectively, assess relevant technologies, and determine strategic partners for service provision. In both public and private areas, municipalities are responsible for managing illegal waste dumps. However, the cost of collecting, cleaning, and restoring these sites is a significant burden on municipalities and their taxpayers [21]. Developing geostatistical tools for mapping and modeling environmental impacts can help improve the effectiveness of environmental law enforcement [22,23]. These tools can facilitate the identification of areas at an increased risk of illegal CDW dumping, assist environmental law enforcement authorities in inspecting specific sites for inspection, and allow them to conserve resources and take more effective action against offenders.

This paper aims to demonstrate the feasibility of mapping and analyzing the contents of illegal waste dumpsites using drones and remote sensing techniques in order to estimate their circular economy potential and the efforts made toward achieving the relevant SGDs. Our demonstration is based on a case study in Israel, which can be applied to other areas in developing countries where illegal dumping is prevalent. Initially, we estimate the potential effects of identifying and treating the different waste materials on the environment and economy on a national level. The paper is organized as follows: Section 2 describes the related literature, Section 3 presents the methods and data, and Section 4 presents the results, followed by the discussion in Section 5; and finally, a short conclusion.

2. Related Literature

Globally, there is an increased interest in finding recycling alternatives and applications with greater commercial value that will lead to the real use of CDWs [24–28]. Generally, CDWs can be categorized as usable or non-usable. Non-usable waste is defined as one that has been contaminated with hazardous waste and is, therefore, unsuitable for reuse. Concrete, ceramics, and bricks are sometimes categorized as non-usable but can be turned into usable waste through recycling. In addition to replacing natural aggregates in mortar and concrete mixtures, these materials may also be used for geotechnical purposes, such as slope stabilization, granular bases, and fillers for sidewalks and roads. CDWs may also contain wood, glass, steel, aluminum, and other materials that can be recycled and reused in various industries, depending on the availability of appropriate treatment facilities and regulations. Furthermore, CDWs may contain a wide range of waste materials derived from a variety of sources, including paint containers and tires. As a result, they may require appropriate disposal or segregation during the separation process [4,7].

A study conducted by Rodríguez-Robles et al. [16] identified several factors associated with illegal landfill sites in the Andalusian region of Spain based on data reduction techniques and geostatistical modeling tools. The study found that 53% of all illegal waste sites were located in municipalities with 10,000–100,000 residents, 60.23% in rural areas and 52% near urban centers. Most (87.73%) of the sites were located near rural roads, 44.31% near highways and industrial zones, and 77.27% within one kilometer of a water source. Remote imaging for detecting and identifying hazardous waste dumping has been investigated in several recent papers [29,30]. According to Lega et al. [30], remote sensing has been used in environmental police investigations involving aerial platforms and an innovative thermography application to detect various illegal activities. Using an integrated approach, it was demonstrated that a thermal imaging tool used to detect environmental contamination could be improved by establishing a database of environmental thermal patterns. In Malaysia, Manaf et al. [27] utilized geospatial analysis methods to trace the illegal dumping of construction waste. The authors described a method for gathering data to create maps that show the type of material and quantity of illegal construction waste, which are useful to local authorities in monitoring illegal dumping. They found that Malaysia suffers from a rise in the illegal dumping of construction waste during periods of accelerated construction. Nevertheless, it is impossible to determine the actual quantity of illegally disposed construction waste in Malaysia, since there is no adequate data collection [27].

In terms of environmental assessment, life cycle assessment (LCA) helps identify the impact of products, systems, and services during their life cycles, for example, from the extraction of raw materials to the time when they are no longer in use (end of life) [31]. The LCA technique has been used for a variety of purposes, including evaluating the various treatment methods for end-of-life products and materials [31,32]. Furthermore, LCA can be used in conjunction with Geographic Information Systems (GIS) and assess location-related impacts. Interfacing GIS and LCA data have primarily focused on bioenergy, land use, and biodiversity, where the specific local conditions are very different [33–35]. Recent studies have defined spatial LCA and reviewed the literature to identify a future research agenda (e.g., Hiloidhari et al., Patouillard et al., and Zainun et al. [36–38]).

Jain et al. [39] developed an analytical framework to assess the environmental impacts of different end-of-life management options for unlined landfills. The study's results indicated that substantial reductions in GHG emissions can be achieved in both waste relocation and in materials and energy recovery scenarios compared to the "do nothing" scenario. It was found that the recovery of metal components from landfilled waste has the greatest impact across nearly all impact categories evaluated, while the emissions associated with mining the waste are negligible compared to their benefits. Seror and Portnov [40,41] utilized ArcGIS to map the risks associated with illegal CDW dumping sites in the Haifa District of Israel. They identified significant factors associated with the accumulation of waste at illegal waste sites, including the distance to the nearest main road, depth of the ravine, and proximity to a forest.

However, sustainability assessments of alternative methods for treating illegal waste are lacking in recent literature. Overall, previous studies have not used drones to identify illegal waste sources and their contents or assess materials from a life cycle perspective. In this research, we are motivated to redirect illegal waste dumps into the economy to ensure the recycling and safe treatment of waste. Among the environmental benefits of treating illegal CDW may be the reduction of system leakage and contamination and natural resource extraction due to increased material recovery. Financial benefits may include increased cost recovery, lower operating costs resulting from increased efficiency, and outsourced costs resulting from the involvement of the private sector. Among the benefits of improved waste collection, sanitation, and water quality are cleaner neighborhoods and public spaces and a reduction in the incidence of waste-associated diseases.

3. Materials and Methods

In our study, we use remote imaging from drones, Geographic Information System (GIS) tools, photography, image processing and LCA data to demonstrate the feasibility of identifying and characterizing the contents of illegal waste dumps, adopting the principles of circular economy (CE). According to Bassi and Dias [42], the idea behind CE is that resource-saving strategies for the reuse, repair, remanufacturing, and recycling of products and their components are essential and enable products to gain a "new life". The CE paradigm is considered an alternative to the traditional linear "take, make, dispose of" model. We view illegal waste as a used material that can be transformed into valuable commodities. Figure 1 below provides a summary view of our multi-method approach:

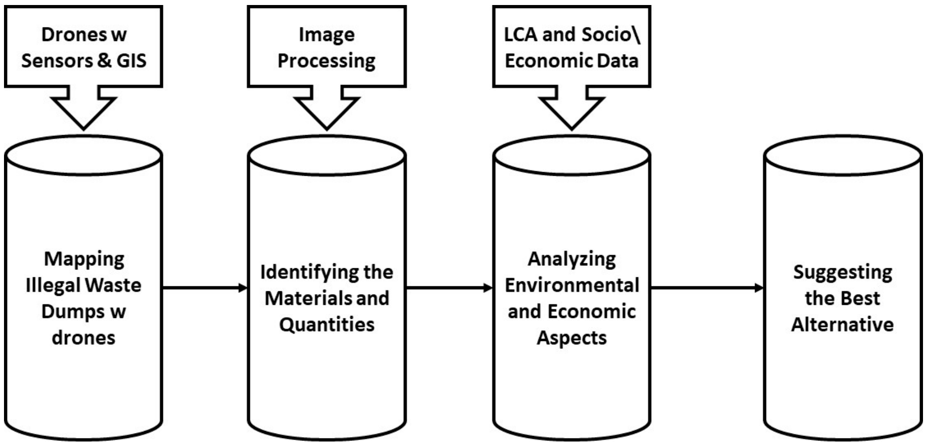

Figure 1. Methods overview. Multi-method approach using remote imaging, GIS, image processing, and LCA data to identify, analyze, and find the best solution for treating illegal waste dumps.

In this study, we used the pilot data from four dump sites in Israel to demonstrate the feasibility of our approach and generate the initial data. The data were collected in 2019 during two days of the drone's operation. The sites are located in the northern part of Israel in the rural area of the Misgav Regional Council with 30,207 residents, covering 180,000 dunams (44,478 acres) [43]. According to the website of the Misgav Regional Council, the following steps should be followed when handling CDW: "Construction waste removal is the responsibility of both the developer and the holder of the construction permit. The waste should be disposed of at a recycling facility, or a landfill approved for this type of waste. It is possible to dispose of the waste using dedicated stopping tools at the construction site or by other means, such as transport by trucks. The waste carrier should issue a permit for entry into the approved site" [43]. Despite the existing guidelines and their enforcement, we discovered many waste piles during a visiting tour we conducted in the area.

During our pilot study, we mapped and analyzed a total area of 3600 square meters. During the preparation stages, "Google maps" was used to map the field in its initial state. Aerial mapping services were provided by "Michnaf Company" for the project. The aerial mapping was conducted using a "DJI Phantom 4" advanced drone featuring a 1-inch CMOS sensor that can take 20 MP photos. An aerial drone flight was conducted from a height of 50 m, with a total of 500 images being captured. Using a double grid, the area was scanned both length- and crosswise. We used a GNSS RTK drone to capture the images, and each image was obtained with an accurate assessment of the area and location. Using their geographic XY landmark location, each pile was allocated to a certain point on a map, a process known as photogrammetric mapping. We were able to combine all captured images into a measurable and connected geographical product with context capture.

The identification of waste piles and different types of waste could only be accomplished using still photos rather than video, to obtain the highest image quality. By taking overlaps of the 70° front and 80° sides, the drone was used to survey the length and cross-section of the area under examination. The images were manually analyzed to identify all waste piles.

We chose to use a drone rather than satellite images due to its ability to measure up to a 2-cm ground sampling distance (GSD). This enabled us to distinguish rock from plastic, wood from concrete, etc. Therefore, we classified and cataloged each waste stream individually and manually to analyze their volumes and pile features. The landmark volume, surface material types, and possible hazards to health and the environment were considered in the mapping phase.

As of today, we are unaware of any technological advancement or automated system that can replace the human measurement of unauthorized waste piles.

We were able to combine all the captured images into a measurable and connected geographical product with context capturing. A three-dimensional model of the scanned area was subsequently created. Using Bentley Context Capture software, the information from the images was converted into a measurable photorealistic 3D model in MESH format. After the model was transferred to ArcGIS, we mapped the piles and volumes of waste. This 3D model is solely based on optical data (images).

This paper focuses on two types of dumpsites: homogeneous waste piles and heterogeneous piles of mixed waste. Through a combination of sophisticated scanning technologies and image processing software, we demonstrated the material classification and its potential impacts. Once the data was analyzed, we created a profile for each dump site. The profile included an economic analysis of the values of different waste streams present at the site and the environmental savings potential for remediating it and recovering recyclable wastes, taking into account the materials' life cycle consequences, transport, and treatment.

4. Results

4.1. Site Analysis

We classified four illegal waste dumps in closed proximity to each other. For these pilots, we established the level of the area, volume, location, and types of waste materials. For each dumpsite, we present the aerial mapping, material classification, and analysis results. We start with two sites of homogenous material, including tires and plastic bags. Figures 2 and 3 present the orthophotos for the two sites. Figure 4 present the orthophotos of illegal heterogeneous waste sites, and Figure 5 present orthophotos of illegal heterogeneous waste sites with mixed waste dump in a larger, spread-out area.

(**a**) (**b**)

Figure 2. Orthophotos of illegal waste dumping sites. Site #1—tire waste; area 9.82 m^2, volume 0.57 m^3. (**a**,**b** are the same site in different resolutions; **b** represent the manual identification).

Figure 3. Orthophotos of illegal waste dumping sites. Site #2—plastic bags; area 17.31 m^2, volume 0.42 m^3.

Sites #3 and #4 represent sites with mixed heterogeneous wastes. Site #3 is an example of concentrated waste, and site #4 is an example of a spread-out dump site.

(**a**)

(**b**)

Figure 4. Orthophotos of illegal heterogeneous waste sites. Site #3—mixed waste dump; area 48.93 m^2, volume 10.64 m^3. Orthophoto (**a**) shows mixed waste, and orthophoto (**b**) shows the materials classification.

Table 1 summarizes the types of materials we identified in mixed waste site #3.

Table 1. Identified materials and their respective surface areas for the mixed waste dump on site #3.

Material	Area (m^2)
Plastic	13.77
CDW	21.42
Metals	4.40
Organic	5.58
Wood	2.67
Tires	0.9
Cardboard	0.19

Figure 5. Orthophotos of illegal heterogeneous waste sites. Site #4—mixed waste dump in a larger, spread-out area; area 346.95 m^2, volume 36.44 m^3.

Table 2 summarizes the types of materials we identified in mixed waste site #4.

Table 2. Identified materials and their respective surface areas for the mixed waste dump on site #4.

Material	Area (m^2)
Plastic	99.11
CDW	214.96
Metals	2.26
Organic	12.78
Wood	0
Tires	2.57
Cardboard	15.27

In order to demonstrate the potential use of the mapping technology, we further estimated the weights of two identified materials at site #3. We translated this into economic and environmental data as a basis for assessing the potential value of materials at the local materials market. In order to estimate the weights, we used area-to-weight conversion factors based on the densities of the materials. Once the types and weights of the materials were obtained, we could use LCA data to assess the environmental impact of recycling vs. landfilling and the economic benefits. For the economic inlays, we estimated the values of four types of materials in site #3, examining the costs and benefits of the treatment and its market prices. Table 3 summarizes the results (based on market prices in shekels converted into USD). As can be seen from the results, the minimum revenue from recycling can cover the maximum cost of treatment.

Table 3. Economic analysis for site #3.

Material	Weight (Tons) *	Cost of Treatment (in USD\ton)	Selling Price in the Market for Recycled Material (in USD\ton)	The Maximum Cost of Treatment (USD)	Minimum Revenue from Recycling (USD)
CDW	3.6	13–26	6–15	93.6	21.6
Metals	0.34	(−87)–0	231–289	−29.6	78.5
Wood	0.16	58–116	173	18.6	27.7
Plastics	0.72	(−147)–(−29.3)		−21.1	105.8
Total				**61.5**	**233.6**

NOTE: The economic data is based on multiple sources (including interviews and informal talks with industry people). The shekel–dollar conversion is based on the ratio of 3.41 IL shekel/USD. Plastics are assumed to be compacted HDPE films. A negative cost indicates a potential profit. * Conversion factors are taken from the US EPA [44].

For the environmental impact assessment, we used data from the GaBi 6 LCA professional database (see Table 4 for the results). It is important to note that the numbers are not adjusted to Israel's energy grid sources mix and shipping distances. Therefore, they only provide an example of the potential impact magnitude measured from two environmental impact categories for the identified materials. The results demonstrate the potential effects of the recycling options compared to landfills in terms of GHG reduction (measured as the GWP; Global Warming Potential) and terrestrial ecotoxicity.

Table 4. Impacts of recycling compared to landfilling on the GWP and toxicity for site #3.

Material	Quantity Mapped (m^2)	Estimated Weight (tons)	Landfilling		Recycling	
			GWP (kg CO_2 eqv)	Terrestrial Eco-Toxicity kg 1,4-DB eq	GWP (kg CO_2 eqv)	Terrestrial Eco-Toxicity kg 1,4-DB eq
CDW	21.41	3.60	169.56 *	8.10×10^{-3} *	14.51 ***	1.3×10^{-3} ***
Wood	2.67	0.16	4.1652 **	1.12×10^{-4} **	0.25 ****	2.3×10^{-6} ****

* GaBi process name: CN: Construction rubble on inert matter landfill ts. ** GaBi process name: AU: Landfill of plywood, flooring (tongue and groove), A-bond, 15 mm (residential) (typical) (EN 15804 C4) FWPA. *** GaBi process name: CH: treatment of waste concrete gravel, recycling ecoinvent version 3.4. **** GaBi process name: AU: Recycling of plywood, flooring (tongue and groove), A-bond, 15 mm (residential) (EN 15804 C3) FWPA.

4.2. National Annual Economic Analysis

Based on the estimates from this pilot, we illustrate the potential economic benefit on a national level for mapping and treating the entire illegal waste in the country. According to the Israeli State comptroller, 6.2 million tons of C&D waste are generated in the country annually, of which 2.19 million tons, or approximately 38%, are dumped illegally in open areas and unauthorized sites [45]. Most of these illegal activities occur near construction sites or at the offenders' places of residence. Most of the dumping is done by individual contractors aiming to decrease their expenses associated with waste disposal or by waste transporters seeking to increase their operational profits. Illegal waste sites in Israel are a major problem, yet they are estimated to store a value of USD 240 million in buried materials [45]. Our analysis used the data from the pilot mapping to calculate the share of the different waste materials on the ground. We then multiplied it by the estimated amount of dumped waste and applied the cost and benefit values obtained from the market players.

According to Seror and Portnov [41], CDW disposal fees range from NIS60 to NIS105 (USD 17–30) per ton, including an environmental tax of approximately NIS5 (USD 1.5) per ton. From our data collection, we estimated the minimal and maximal prices per ton material and multiplied it by the annual waste quantity. Table 5 summarizes the price ranges and the annual weight estimates (projections are based on the pilot findings).

Table 5. Economic analysis of the price ranges and annual weight estimates on a national level.

Material	% of the Total Illegal Waste	Annual Weight (Tons) *	Max Cost (USD) Per Ton **	Min Cost (USD) Per Ton **
Plastic	37%	815,694	−147	−29.3
Construction	51%	1,113,131	26.4	13.2
Metals	2.30%	49,456	−88	0
Organic	5.20%	114,759	32.3	29.3
Wood	0.90%	19,237	117.3	58.7
Rubber	0.60%	14,188	263.9	205.3
Cardboard	2.90%	63,534	32.3	29.3

* Based on the multiplication of the % share mapped at our sites multiplied by 2.19 million tons dumped illegally. The negative signs for the cost indicate a positive economic benefit (income). ** The shekel–dollar conversion is based on a ratio of 3.41 IL shekel/USD.

We constructed two waste treatment scenarios and assessed their economic outcomes: one is based on the existing situation, assuming that if the sites are cleaned up, the waste is transported and landfilled (with a minimum cost of USD 26.4 and a maximum cost of USD 161.3); the second scenario involves separation by material for recycling, where possible. See Table 6 for a summary of the results.

Table 6. Economic analysis based on two different waste treatment scenarios.

Scenario	Description	Annual Weight on the Ground in ton	Minimum Cost/Benefit (Million USD)	Maximum Cost/Benefit (Million USD)
Existing (1)	Mixed waste is collected and transferred to landfill	2,190,000	57.8	353
Separation and treatment by material (2)	Plastics	815,694	−23.9	−119.6
(2)	C&D	1,113,131	14.7	29.4
(2)	Metals—steel mainly	49,456	0	−4.3
(2)	Tiers—Rubber	14,188	2.9	3.7
(2)	Wood	19,237	1.1	2.3
(2)	Others	178,293	5.2	5.7
(2)	Total for all materials		0.04	−82.8

Note: The negative signs for the costs indicate a positive economic benefit (income).

Based on our estimate, we can conclude that, at the very least, proper waste disposal can reduce treatment costs by USD 58 million and reach zero. Moreover, it has a potential to generate up to USD 82.8 million in profits.

4.3. SDG Analysis

In this section, we demonstrate how this work can contribute to the relevant SDG. In some cases, the contribution is described qualitatively and, when possible, quantitatively. See Table 7 for the sustainable development goals analysis.

Table 7. SDG analysis.

Target	Indicators	Potential Contribution
8—Promote sustained, inclusive, and sustainable economic growth; full and productive employment; and decent work for all.		
8.4—Improve progressively, through 2030, global resource efficiency in consumption and production and endeavor to decouple economic growth from environmental degradation, in accordance with the 10-Year Framework of Programs on Sustainable Consumption and Production, with developed countries taking the lead.	*8.4.1 Material footprint, material footprint per capita, and material footprint per GDP.* Material Footprint (MF) is the attribution of global material extraction to the final domestic demand of a country. The total material footprint is the sum of the material footprints for biomass, fossil fuels, metal ores, and non-metal ores.	Material extraction will be reduced by an amount of 2,190,000 tons if the identified materials on the ground are recycled and virgin materials are saved.
	8.4.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP. Domestic Material Consumption (DMC) is a standard material flow accounting (MFA) indicator that reports the apparent consumption of materials in a national economy.	The DMC will not change, only the origin and impact of the materials.
12—Ensure sustainable consumption and production patterns		
12.4—By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed-upon international frameworks, and significantly reduce their release into the air, water and soil in order to minimize their adverse impacts on human health and the environment.	*12.4.2 Hazardous waste generated per capita and proportion of hazardous waste treated, divided by type of treatment.*	There are several types of hazardous waste, e.g., tires, asbestos, etc. In another location (which is not reported in the results) away from the pilot area, we also observed a homogeneous side pile of asbestos on the ground. By identifying and treating illegal hazardous waste, our approach will contribute to an increase in hazardous waste treatment, as defined by the indicator.
12.2 By 2030, achieve the sustainable management and efficient use of natural resources.	*12.2.1 Material footprint, material footprint per capita, and material footprint per GDP.* This indicator is calculated as the raw material equivalent of imports (RMEIM) plus domestic extraction (DE) minus raw material equivalents of exports (RMEEX).	In Israel, aggregates are the most commonly extracted material. As a result, by recycling CDW back into aggregates, the need for local virgin extraction could be reduced by 1,113,131 tons.
	12.2.2 Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP.	

Table 7. *Cont.*

Target	Indicators	Potential Contribution
12.5—By 2030, substantially reduce waste generation through prevention, reduction, recycling, and reuse.	*12.5.1 National recycling rate, in tons of material recycled.* For the purposes of this indicator, the National Recycling Rate will be defined as the quantity of material recycled in the country plus quantities exported for recycling out of the total waste generated in the country, minus imported material for recycling.	Similarly, Israel would improve both indicators if 2,190,000 tons of waste were recycled rather than dumped on the ground or disposed of in landfills. In addition to calculating the change for each material individually, it is also possible to calculate the overall change. For instance, if 2.2 million tons of illegal waste are recycled out of 6 million tons generated yearly, this would mean a 36% increase in the recycling rates.
Other SDGs		
11.6—Reduce the environmental impacts of cities.	*11.6.1 Solid waste management* *The proportion of municipal solid waste collected and managed in controlled facilities out of the total municipal waste generated.*	The majority of construction waste is generated in cities, so the responsibility should be attributed to each city. Furthermore, the municipality is usually responsible for the treatment of illegal waste. Therefore, if waste is managed more effectively, the proportion of managed waste will increase.
3.9—By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination.	*3.9.3 Mortality rates attributed to unintentional poisoning.*	It is possible to create local poisoning conditions or groundwater pollution as a result of certain hazardous waste. The risk of such events can be reduced by removing hazardous materials (asbestos, tires, organic waste from farms, etc.). In this pilot, we identified 114,759 tons of organic waste and 14,188 tons of rubber from tires that could be prevented from leaching. Since it is beyond the scope of this indicator, we do not estimate the potential reduction in mortality rates due to pollution. It is also possible to use the estimated future LCA result for human toxicity as an indicator.
6.3—By 2030, improve water quality by reducing pollution, eliminating dumping, and minimizing the release of hazardous chemicals.		Similar to the above, our work can generally help reduce hazardous materials in open areas and, therefore, the risk of water pollution.
15.3—By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought, and floods, and strive to achieve a land degradation-neutral world.	*15.3.1 Proportion of degraded land over total land area.*	Upon removal of the illegal waste, some of the land may be able to be restored. Consequently, it is possible to estimate the land area from the estimation of the area size derived from mapping.

5. Discussion

Our initial results suggest that there are economic and environmental potential benefits in mapping illegal waste from the air and identifying local recycling opportunities when possible. First, we demonstrate the feasibility of our approach using the pilot data from the technical perspective and, subsequently, how the generated data can be further analyzed. Our approach requires multiple data sources using drones and image processing and additional data sources related to the economic and environmental parameters of the identified materials.

According to ISWA [19], management of the social impacts, risks, and opportunities of illegal dumpsite closure involves several core activities, which must be built into planning, integrated into the timeline, and budgeted for. These include (1) stakeholder identification, mapping, and engagement; (2) assessment, diagnostics, and analysis; (3) the development and discussion of proposals; (4) the implementation of solutions; (5) complementary activities, such as training; (6) operation and maintenance; and (7) monitoring and evaluation.

The approach and results presented here can help implement stages 1–4 and 7. The pilot showed the benefits of multidisciplinary tools and methodologies that can assist in diagnostics and analysis, provide economic data for cleanup proposals, and, of course, enable the monitoring and evaluation of the area after the cleanup. Our method provides a tool for faster monitoring and evaluating illegal waste dumps, saving time and money for the municipalities (in our case study, the Misgav Regional Council) and their stakeholders. In the future, when the tool is further automated, stages 2 and 3 can be executed more efficiently.

Our current research is intended to demonstrate the potential of our mapping capability and its contribution to SGDs; however, the research has some limitations: first, it is based on a few small pilots of waste mapping in Israel's open spaces. Our next stage will be to evaluate the method's operation for larger and more complex areas of open dump sites.

Second, so far, the mapping was conducted for above-ground waste only and assumed the pile underneath was homogenous; however, there are concerns about not being able to identify waste streams in heterogeneous piles, as well as receiving inaccurate measurements of piles and material volumes. To address this, we used manual processing and plan to switch to automated processing and field data comparisons in the future. Artificial intelligence and picture recognition will be used in future research for automatic identification. Furthermore, there have been concerns about drone capabilities being limited by airspace and the inability to fly and the costs of mapping large areas. Future studies will also apply the use of the latest computer vision object classification, detection, or segmentation algorithms to efficiently automate this process using a single economical camera sensor.

Lastly, currently, there is no technology to penetrate waste piles buried underground, which might result from illegal waste dumping over long periods of time, continuously adding new waste to existing waste piles.

On the theoretical side, our work contributes to the methodological approach while testing its feasibility for identifying illegal waste materials in advance by using drones and optimizing its economic and environmental potential for cleanup and local treatment. On the managerial side, this work demonstrates the potential for policy-makers to invest in adopting such mapping tools and generate economic benefits, develop a local circular economy, and ensure that adverse environmental impacts are avoided. From an economic perspective, site-specific data, such as materials, volume, and weight, can also serve different stakeholders in better preparing for tenders and bids for the removal and cleanup stage (by obtaining a more accurate estimate of the waste volume), thereby saving money and resources.

6. Conclusions

This feasibility study results supported our initial assumption that drones can be used as beneficial tools for the identification of different types of waste deposited on the ground in open areas of illegal waste sites. We find that manual identification in the first stage is feasible and applicable and can be further used for economic and environmental assessments of circular economy potential. Through a case study in Israel, we demonstrated the potential for significant economic savings associated with the cleanup and treatment of illegal CDW.

Although this study was conducted in a specific region of Israel, it offers a useful starting point for developing similar risk and opportunity assessments for other areas in Israel and other countries by identifying areas that are at high risk of illegal CDW dumping. Using this framework, we were able to analyze the economic and environmental potential of different waste streams and their contributions to a circular economy and the various Sustainable Development Goals. As a result of our SDG analysis, we found that the subject of illegal waste is relevant to several SDGs. However, it is often the case that the level of indicator data is too aggregated; the indicators should be adjusted in order to clarify their contribution and allow for more detailed data such as ours to be assessed using quantitative SGD metrics.

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