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A Systematic Review of the Latest Research Trends on the Use of Satellite Imagery in Solid Waste Disposal Applications from 2012 to 2021

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Abstract: There is currently no review article on the role of remote sensing (RS) tools on waste disposal site (WDS) applications. Permanent waste disposal is the world's most commonly used solid waste management method, and a specific review is warranted. To investigate research trends and to identify knowledge gaps on the use of satellite-based RS in WDS applications, 170 studies published over the last decade, from 2012 to 2021, were examined and classified using a bibliometric approach. Results are discussed with respect to relevancy, satellite types, study origins, RS analytical methods, and applications. Out of 72 short-listed studies, 44.4% were carried out in Asia, followed by Europe with 18.0%. Asia is also a leading region in the use of multiple satellite products. Only two satellite products were utilized in African studies. The absence of local satellites could potentially be the reason behind the sole use of global satellite imagery. Globally, Landsat contributed 70.8% of the total studies. Sentinel products represented only 8.3%. About 44% of the studies used various RS indices when addressing WDS-related issues. The majority of studies (56%) applied image classification methods to study changes in land use and land cover. The temporal trend reveals a general increase in the total number of studies, particularly for suitable site detection and disposal-site-induced anomaly detection. This review directly addresses the knowledge management aspect of data-driven solid waste management.

Keywords: waste disposal sites; landfills; remote sensing; satellite imagery; image classification; solid waste management

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1. Introduction

Solid waste management (SWM) is an important sustainability issue and relates to more than half of the United Nation's sustainable development goals directly or indirectly. The importance of SWM on public health, environmental impacts, and socio-economic development are well recognized [1–3]. For example, Espuny et al. [4] reviewed 1986 SWM studies from 2005 to 2018 to examine various SWM analytical tools and management systems' performance throughout the world. Espuny et al. [4] suggested that qualified information on SWM can better support decision-makers by minimizing environmental footprints and improving the quality of life in urban areas. Permanent land disposal, incineration, composting, and recycling are popular SWM methods.

Increased population growth and rapid urban development have brought new challenges to SWM in both developing [5–7] and developed countries [8–10]. In situ data collection and frequent field monitoring of environmental analysis are gradually replaced with newer and more efficient methods, such as remote sensing (RS) and Geographical Information System (GIS) techniques. Unger et al. [11] systematically applied RS techniques with extended area coverage and effectively modeled and evaluated environmental resources. Alexakis et al. [12] integrated RS data and GIS analysis and demonstrated how these tools were used in landfill siting to better address environmental sustainability and support urban municipalities. Chen et al. [13] used GIS to map and evaluate the number of designated smoking areas in 12 Canadian campuses to mitigate the litter coming from cigarette butts. Recently, Karimi et al. [14] applied both RS and GIS to study regionalization of a waste management system in Canada. Although RS data are freely accessible in most of the regions, cloud coverage and other limitations are also discussed in review studies [15–17].

SWM researchers soon realized that the use of these advanced analytical techniques is important to evaluate, design, and operate a SWM system that is built upon a data-driven waste policy [18–20]. The incorporation of RS imagery and GIS in different aspects of SWM has gained popularity [21–23]. Recent applications include mapping of dump sites [24,25], optimization of regionalized waste management systems [26–28], and analysis of waste collection systems [29,30].

Given the practical importance of the subject, there are published review articles on the roles of these data-driven techniques in SWM applications. Dutta and Goel [31] reviewed the use of RS data in a wide range of SWM issues in India from 1996 to 2014, including waste generation and sorting, transfer and transport, process and recovery, collection and storage, and disposal. Singh [22] examined the applications of both RS and GIS techniques in SWM using multiple case studies and indicated that geospatial analysis and optimization using these techniques are advantageous, particularly in developing countries. Ahmed et al. [32] conducted a review to identify the feasibility of nutrient extraction from solid waste and to evaluate various analytical techniques, including RS, GIS, Unmanned Aerial Vehicles (UAVs), and life cycle assessments, on the quantification of environmental impact originating from improper SWM. However, none of these review articles specifically addressed the role of RS in waste disposal site (WDS) applications on a global scale. Permanent waste disposal, or landfilling, is the ultimate end-point for all SWM systems. Information on how to better utilize landfill technology is, therefore, a priori to a sustainable SWM.

GIS techniques, such as network analysis, are versatile but are well established and well reported in the field of SWM [33–35]. On the other hand, there have been many developments in the applications of RS recently, as discussed in the following sections. The spatial and temporal resolution of freely accessible RS data have dramatically improved in the past decade, and a specific review is warranted. The review objectives are to investigate the latest research trends, and to identify knowledge gaps in the use of satellite-based RS in WDS applications from 2012 to 2021. This mini review study contributes to the comprehensive understanding of the state-of-the-art RS techniques related to WDS applications during the past decade and fills the knowledge gap on the development of data driven waste policy within an expert system. Identified trends and knowledge gaps are separately discussed concerning satellite types, study origins, RS analytical methods, and applications.

2. Materials and Methods

2.1. Collected Studies

A total of 170 English language peer-reviewed journal articles, excluding conference papers, were collected using the Web of Science database. Bibliometric analyses suggest that Web of Science database is generally more selective [36,37]. Articles were collected using two Boolean strings ("remote sensing" and "disposal") or ("remote sensing" and "landfills") over 10 years, from January 2012 to December 2021. We have selected simple and generic keywords, so our search is broad and inclusive. A 10-year study period is defined because there has been a drastic increasing trend in the use of RS techniques in recent years, which is not addressed in other related review papers [22,32].

While the two Boolean strings allowed a wide spectrum of studies using satellite-based RS in WDS, the results also included studies which were not well aligned with the study objectives. We then used a systematic approach to further screen the articles. In additional to the "front page" filtering criterion [38], potential matches are individually reviewed. Criteria such as relevancy, RS data type, and study type are considered, allowing us to identify specific trends and knowledge gaps. A schematic workflow of this review study is shown in Figure 1, and a total of 98 out of 170 studies (57.7%) were screened. Brief discussions on the screened studies are separately reported in Section 2.2.

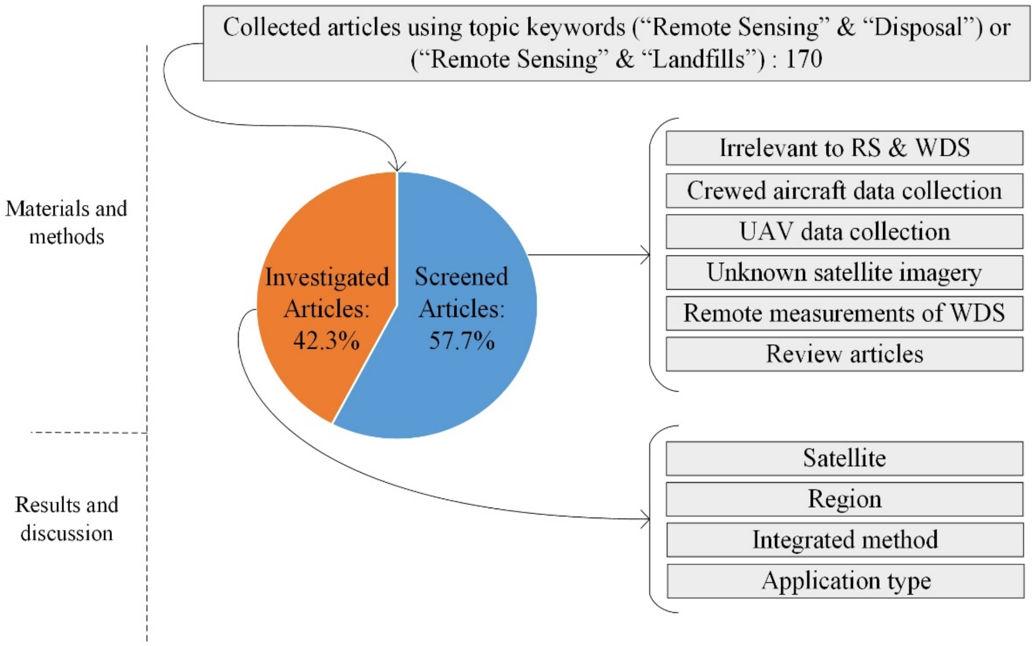

Figure 1. Workflow of current study.

2.2. Data Processing and Screening

2.2.1. Irrelevant to the Integration of RS and WDS

As shown in Figure 2, 60% of screened articles were not directly related to the specific study objectives. For example, Blanco et al. [39] used a combination of site measurements, surveys, and GIS analysis to classify and map agricultural plastic waste in an Italian agricultural region without adopting any satellite RS imagery. Wang et al. [40] used Landsat satellite imagery and a supervised classification method from 1984 to 2017 to determine the land cover change in the Zhoushan Archipelago region of China without discussion on WDS. Other studies used RS satellite imagery to evaluate evapotranspiration as a part of the water budget in marshlands [41] or agricultural lands [42]. In addition, future space debris environment and end-of-life satellite disposal operations were discussed by Ren et al. [43] and Bertrand et al. [44], respectively. These studies are not related to the adoption of satellite-based RS in WDS and were thus removed.

2.2.2. Crewed-Aircraft-Based Data Collection

Around 14% of removed articles (Figure 2) used crewed aircraft for data collection and thus are screened. For example, Cusworth et al. [45] identified California methane emission contributors using aircraft equipped with Next Generation Airborne Visible/Infrared Imaging Spectrometer (AVIRIS-NG) for more than 436 waste facilities and landfills from 2016 to 2018. Similarly, AVIRIS-NG was adopted to investigate and map methane clouds over 272,000 industrial facilities, including oil and gas, manure, and waste management sectors, from 2016 to 2018 [46]. Methane emissions from more than 20 facilities, including landfills, composting operations, and wastewater treatment plants, in San Francisco Bay Area from 2015 to 2018 were estimated using a mass-balanced technique from airborne imageries [47].

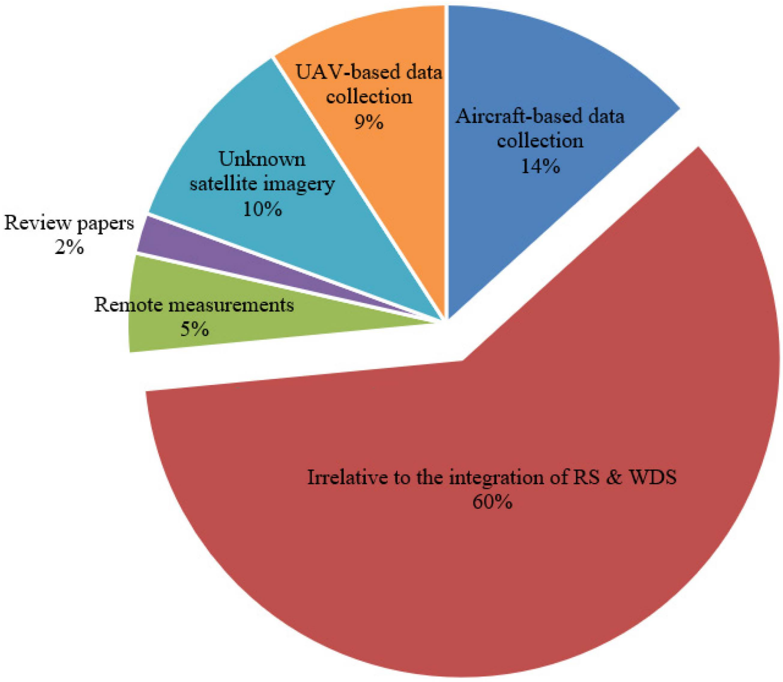

Figure 2. Screened articles in current study.

2.2.3. UAV-Based Data Collection

UAVs have also been used by researchers as an affordable tool to collect imagery from solid waste facilities [48–50]. UAV-based data collection articles comprised around 9% of the screened articles (Figure 2). UAV-based data collection is often limited to a small study area, typically an engineered landfill. For example, thermal infrared cameras onboard UAVs were employed to detect concentrated fugitive methane sources at two Danish landfills for two consecutive years in 2015 and 2016 [51]. Interpretations of multiple thermal maps obtained from UAV flights over two Italian landfills showed an association between biogas leakage and higher surface temperature compared to neighboring regions [52].

In addition to thermal imagery, UAVs were also used to visually interpret environmental anomalies associated with WDS. For example, UAVs were used to capture the environmental footprints of a catastrophic landfill landslide in Shenzhen, China, in 2015 [53]. UAV-based aerial images were collected after a Japanese earthquake in April 2016 to quantify the scale of disaster waste generation [54].

2.2.4. Unknown Satellite Imagery, Remote Measurements, and Review Papers

As shown in Figure 2, around 10% of screened studies used unknown or unidentified satellite imagery [55–57]. In addition, 5% of screened studies measured and monitored environmental attributes at WDS without the use of satellite imagery [58,59]. For example, Fredenslund et al. [60] used instruments mounted on two vehicles to measure downwind concentrations of methane gas originating from landfills at distances ranging from over one to three km. Lastly, about 2% of screened studies were review articles focusing on the various aspects of RS techniques on SWM. For example, Ahmed et al. [32] conducted a review to highlight nutrients and energy extraction potentials from various waste fractions.

2.3. Further Investigated Articles

Among all 170 collected articles, 72 articles (42.3%) adopted satellite-based RS in WDS applications and were selected for further analysis. The research trends and knowledge gaps are separately discussed according to the type of satellites (Landsat, Sentinel, Terra), study region (Asia, Africa, North and South America), integrated method (“Image Classification” and “RS Indices”), and WDS application types (“WDS detection”, “Waste Disposal Site Induced Anomaly detection” and “suitable site detection for future WDS”).

The potential classifications might be beneficial to explore the potential drawbacks of the absence of a regionally launched satellite on the use of the technology.

NVivo package (version 12) was used for qualitative data analysis, mind-map development, study classification, and coding in this mini review. NVivo is designed to incorporate data from different sources, use management and visualization tools, and extract quantitative research-oriented results [61]. NVivo is commonly used in the solid waste management field for data analysis and review [62–64].

3. Results and Discussion

3.1. Satellite Based RS for WDS by Regions

Figure 3 explores how different satellite products are adopted in WDS studies in different regions. Out of 72 short-listed studies, 32 (44.4%) were carried out in Asia, followed by Europe with 13 studies (18.0%). Asia has a larger continental area (around 31 million km^2), denser population density (over 150 people per km^2), and the highest world population share (around 60% of the total global population). It appears that the use of satellite-based RS is quite popular in Asia. North America has published 10 studies during the study period. Given a relatively higher labor cost in North America and the popularity of landfill disposal, studies on the use of RS in WDS applications in Canada and the United States are recommended. Only five studies were published in South America, or about 6.4 times fewer than in Asia during the same period. Although both Asia and South America have a higher number of developing counties, their interest in the use of satellite-based RS in WDS contrasts sharply. It is, however, important to note that only Web of Science-indexed studies are considered in this study. Many researchers in developing countries may write in the local language and publish in local journals, thus are not included in Figure 3.

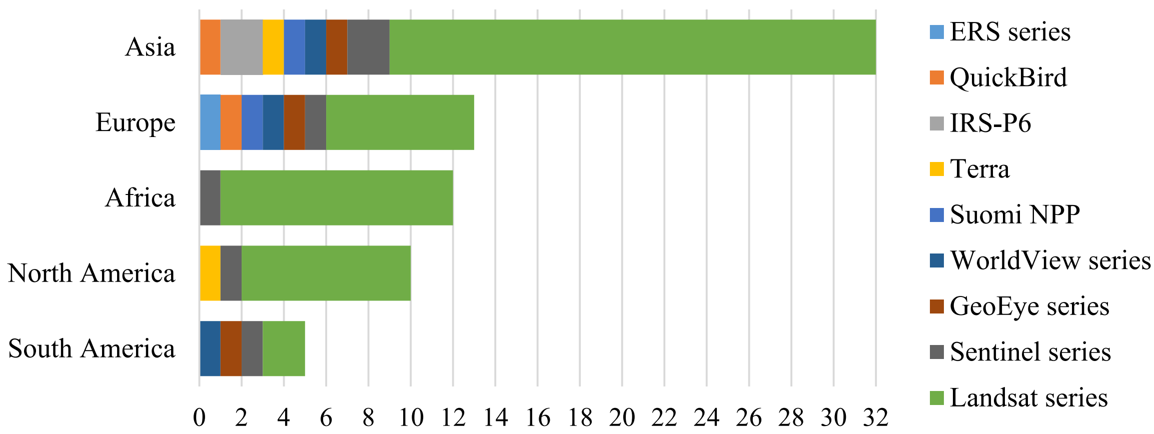

Figure 3. Number of studies in different regions classified by satellite products from 2012 to 2021.

Aside from the total number of studies, Asia is also a leading region in the use of multiple satellite products. Satellite imagery sources are quite diverse in Asia and Europe, with eight and seven satellite products, respectively. The adoption of multiple satellite products might in part be due to the newly launched satellites with diversified data coverage in multiple regions. For example, the Indian satellite IRS-P6 contributed to Asian studies recently (Figure 3). IRS-P6 is equipped with three instruments LISS-4, LISS-3, and AWIFS, collecting images in the visible and near-infrared spectrum, with a spatial resolution of 5.8 m, 23.5 m, and 56 m, respectively [65]. Similarly, ERS series contributed to European studies in the past, which was launched by the European Space Agency (ESA) during the early 1990s with eight instruments for the earth and ocean environmental monitoring [66]. Africa is the second-largest and second-most populous continent on earth, and Africa ranks third after Europe, with a total of 12 Web of Science indexed studies (16.6%). A closer look at Africa, however, reveals that only two satellite products were utilized, as 11 out of 12 studies are from Landsat products. The absence of local satellites might be the reason behind the sole use of global satellite imagery such as the Landsat and Sentinel series. Almost all studies in North America, nine out of ten, used satellites that were launched by the United States (Landsat and Terra). Although there were fewer studies in South America, the selection of satellite products was quite diverse, including Landsat, Sentinel, GeoEye, and Worldview series, suggesting no dominating preference for satellite products.

As shown in Figure 3, the Landsat series are the leading satellite products favored by researchers on WDS studies. Globally, Landsat contributed 51 or 70.8% of the total studies during the study period. Landsat series are a suitable global choice probably due to their free public access, comprehensive archived data, and reasonable time and spatial resolution. Landsat satellite has continuously monitored the entire earth's surface for almost five decades (the first satellite was launched in 1972), allowing in-depth studies related to climate change and long-term impacts on environmental policy [67–69]. The temporal resolution of 16 days [70] and moderate spatial resolution (varies in different spectrums and platforms) make the product suitable for various WDS studies. Sentinel products from Europe [71] are the second-ranked most frequently used satellite products, with a total of six studies (8.3% of the total studies). Global coverage, free data, and higher spatial and temporal resolution (compared to the Landsat series) make them a suitable choice for the scientific community, and researchers across the globe have used Sentinel products in their studies. However, due to its more recent launch date (after 2016), there might not be sufficient recorded data for longer-term studies. We expect the popularity of Sentinel products to increase in the next decade.

The remaining satellite products did not significantly contributed to WDS studies (cumulatively less than 21% of the total studies). For example, Terra is versatile and consists of five different instruments, ASTER, CERES, MISR, MODIS, and MOPITT, with different objectives [72]. However, this review shows only two studies during the study period from North America and Asia. It appears that ultra-high spatial resolution is not the sole consideration for researchers in the selection of satellite products. For example, the ASTER instrument onboard Terra collects high-resolution visible and thermal images, ranging from 15 m^2 to 90 m^2 [73]. ASTER is also suitable for obtaining surface temperature and elevation [73]. GeoEye series are another commercial satellite with spatial (visible range) and temporal resolution of 1.65 m and 3 days, respectively [74]. Despite the high spatial and temporal resolution of commercial satellites offered by Maxar Technologies (QuickBird, WorldView, and GeoEye) [75] the charges associated with their image acquisition made them less publicly accessible. Only seven studies in three regions (Asia, Europe, and South America), or about 9.7% of the total studies, adopted these satellites with user fees.

3.2. Integrated Methods Used for RS in WDS Studies

Two major approaches, "RS indices" and "image classification", were used to integrate RS data in the reviewed articles. About 44% of the studies used various RS indices in addressing WDS-related issues (Figure 4a). For example, Sarp and Ozcelik [76]) used Land Surface Temperature (LST), Normalized Difference Moisture Index, and Soil Adjusted Vegetation Index (SAVI) to quantify the environmental effects of the accumulated waste in a quarry site in Isparta, Turkey. Similarly, higher LST values were used to identify methane gas hotspots in Canadian landfills [77] and various landfill sites in Vietnam [78].

The major share of studies, 56% (Figure 4a), applied image classification methods in their WDS studies. For example, Agapiou et al. [79] used the Spectral Angle Mapper classification algorithm to identify a similar reflectance spectrum of the olive oil mill WDS areas on the Island of Crete, Greece. Likewise, Chen et al. [80] classified and detected demolition waste in Beijing, China, by differentiating the spectral signature of vegetation cover and demolition waste, as well as addressing the irregular shape of piled construction waste.

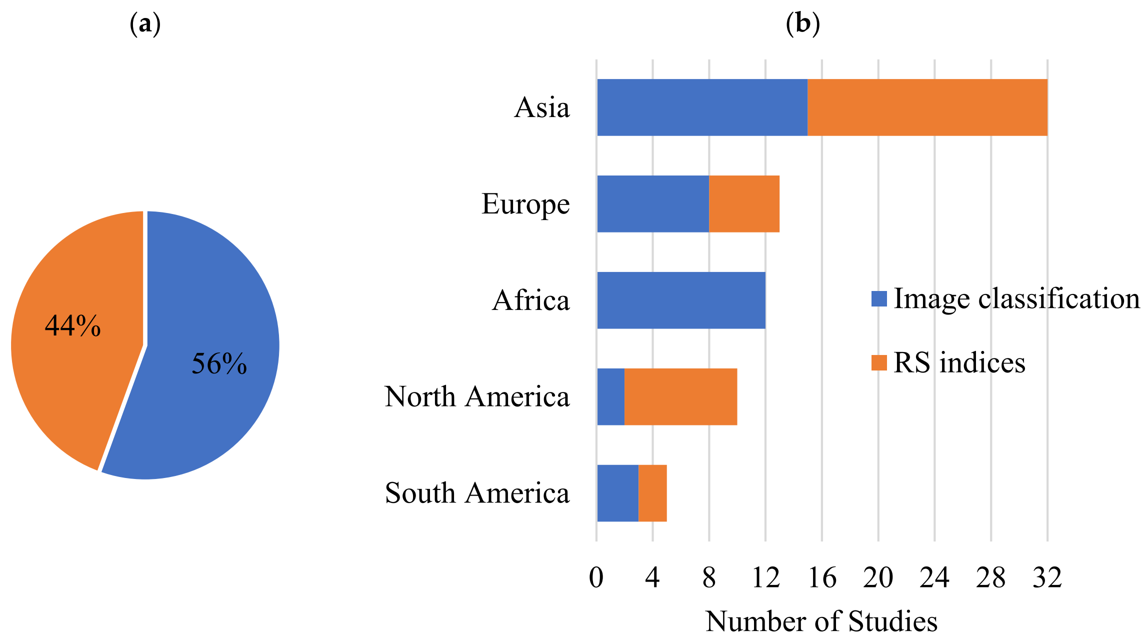

Figure 4. (**a**) Number of studies in different regions classified by the type of integrated method in satellite imagery from 2012 to 2021 (**b**) Overall RS integrated methods share from 72 articles.

The distributions of the WDS studies are shown in Figure 4b. The total number of studies that integrated RS indices in Asia and North America is higher than studies with image classification, as opposed to Europe and South America. This might be due to different policies in different regions. For example, the Environmental Protection Agency in the USA provides detailed information on greenhouse gas emission standards, which should be followed by methane gas emitters, such as landfill operators [81]. As such, determining the major methane contributors would be of higher importance. RS indices, such as LST and Normalized Difference Vegetation Index (NDVI), could serve as suitable indicators for these WDS sites [82–84]. On the contrary, most European, African, and South American countries face landfill site suitability issues due to urbanization and overall lack of accessible lands [33,85,86]. Thus, image classification is frequently adopted to identify different land uses and land covers, such as agricultural lands, water resources, protected areas, faults, and hazardous zones. Identification of these classes helps in locating landfills in optimal places with lower environmental footprints and minimum adverse health effects [87–89].

It is noteworthy to mention that Africa is the only region where RS indices are not used at all (Figure 4b). This could be attributable to the research interests of integrated studies which solely focused on the outcomes of the image classification. For example, Hawash et al. [7] showed how land cover classes changed, including the expansion of a local landfill, from 1999 to 2018, over Port Sudan and the Red Sea. Similarly, Kamh et al. [90] analyzed the urban growth in the Hurghada area since the 1980s to assess the anthropogenic activities using the Landsat series and LULC classification method. They reported that around 4.5 km^2 of landfilling area was added over the edges of coastal areas as a result of urbanization and increased tourism industry [90]. On the other hand, only 20% of North American studies utilized image classification. Image classifications were commonly conducted in North American WDS studies in the past, and the interest appears to have shifted to the use of RS indices.

3.3. Type of Application on WDS Studies from 2012 to 2021

Specific applications of the WDS studies are further examined. Reviewed studies are categorized into three different groups according to their applications, including WDS detection (WDSD), suitable site detection for WDS (SSWD), and WDS-induced anomaly detection (WDSA).

WDSD group consists of studies identifying places that are susceptible to probable WDS. For example, Yoshida et al. [91] used a combination of RS imagery, including ASTER, to identify potential changes in land elevation and land cover attributable to the presence of landfilling activities and mining sites from 2000 to 2010 in Germany. Gill et al. [92] used aggregated surface temperature data to identify potential locations of dumpsites in Kuwait from 10-year Landsat imagery. WDSD only represents 13% of total reviewed papers (Figure 5a) and is presented for five out of ten years (Figure 5b). This might be due to the difficulties associated with the heterogeneous nature of accumulated waste in WDS, which often cannot be captured by focusing on a particular material using a specific spectral signature.

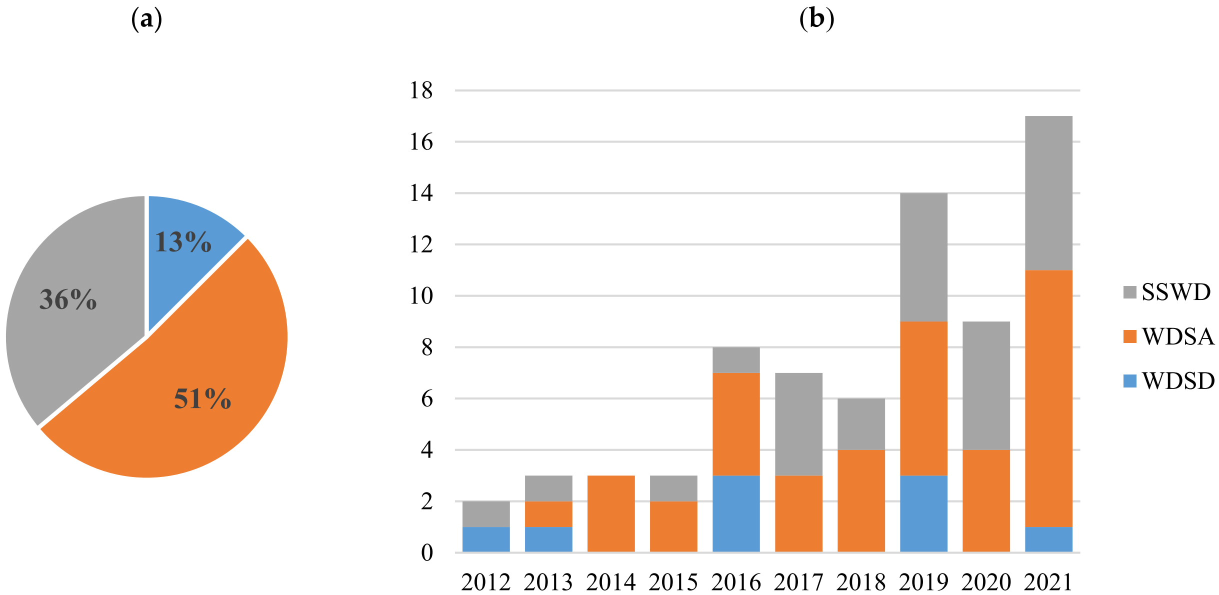

Figure 5. (**a**) Type of RS application during the study period (**b**) Overall RS applications share in the reviewed articles. SSWD = Suitable Site detection for Waste Disposal site; WDSA = Waste-Disposal-Site-Induced Anomaly detection; WDSD = Waste Disposal Site Detection.

SSWD ranked second among applications using RS images, contributing to around 36% of the total reviewed studies (Figure 5a). SSWD studies typically consider various environmental constraints, such as water bodies [93–95], soil type [95,96], ground elevation [94,97,98], and slope [35,94,99], in their siting analysis. Most of the SSWD studies used multicriteria decision-making tools, such as the analytical hierarchy process and fuzzy logic algorithm, to determine the final rankings [18,100,101].

Over half of the studies, or about 51% (Figure 5a), used RS to identify environmental and geophysical changes caused by WDS. For example, LST is acquired for over 17 years in an American landfill to pinpoint the locations of landfills' subsurface fires [83]. Long-term satellite observations on thermal characteristics, such as higher thermal gradients and LST, can determine the waste-contaminated [102,103]. In addition, areas with degraded vegetation cover in proximity to WDS were estimated using a combination of vegetation indices, such as NDVI, SAVI, and MSAVI [104–106].

The temporal research trends can be observed in Figure 5b. A general increase in the total number of studies, particularly for SSWD and WDSA, can be observed in recent years. For example, the total number of studies ranges from two to three before 2016, while it fluctuates between six and seventeen in recent years. This might be due to the introduction of newly launched satellites, such as the Sentinel series [107–109]. In addition, an urgent need for the replacement of conventional in situ monitoring with innovative methods addressing the rapid global urban expansion and population growth is another potential factor [76,106,110].

A noticeable reduction in the total number of studies happened in 2020, Figure 5b. This may be related to the global spread of COVID-19 in 2020 and associated lockdowns. A considerable number of waste studies have focused on solid waste generation characteristics [3,111,112] and disposal behaviors [113–115] during the pandemic rather than selection and ranking of WDS.

3.4. Limitations

Only peer-reviewed Web of Science indexed publications during the last decade are considered in this review study. Web of Science is one of the most widely used databases for bibliometric analyses and is also more selective than Scopus [37]. Alternative scholarly databases, such as Dimensions, Google Scholar, and Microsoft Academic [36], are not considered. Conference papers, scholarly monographs, self-archived book chapters, and other unrefereed studies are also excluded in this mini review. A few unpublished industrial reports were deemed meritorious; however, they were not included in this mini review due to their poor availability to the general public. Authors in developing countries who prefer local journals and studies from non-English speaking countries may be underrepresented in this review as only English articles were considered. Researcher's merits, affiliation, and network were not explicitly considered in this study, but they are recommended in future bibliometric studies to provide more context on research collaboration.

4. Conclusions

This mini review investigates the latest research trends and identifies knowledge gaps in the use of satellite-based RS in WDS applications from 2012 to 2021. Permanent waste disposal is the ultimate endpoint for all SWM systems. Given its great practicality, the use of RS techniques in WDS studies has gained popularity. Most RS sets are freely available, and analysis of RS data helps develop data-driven waste policy and reach a more sustainable waste management system. Using two simple Boolean strings, a total of 170 Web of Science-indexed journal articles were collected. NVivo package was used for qualitative data analysis. Criteria such as relevancy, RS data type, and study type are used to screen studies.

We found that the use of satellite-based RS was popular throughout Asia during the last decade. Out of 72 short-listed studies, 44.4% were carried out in Asia, followed by Europe with 18.0%. More studies on the use of RS in WDS applications in North America are recommended. Only five studies were published in South America, but they used diversified satellite products, suggesting no dominating preference for satellite products. Asia is also a leading region in the use of multiple satellite products. African studies, on the other hand, utilized only two satellite products. The absence of local satellites may be the reason behind the sole use of global satellite imagery. Globally, Landsat contributed to 70.8% of the total studies during the last decade, probably due to a free and comprehensive archived data set. A long-archived data set allows in-depth WDS study related to climate change and long-term impacts on environmental policy. Sentinel products are the next most popular satellite products, representing 8.3% of the total studies. The popularity of Sentinel products may increase in the next decade due to their better spatial-temporal resolutions. About 44% of the studies used various RS indices, such as LST and SAVI, when addressing WDS-related issues. The majority of studies (56%) applied image classification methods to study changes in land use and land cover. African studies only used image classification in WDS studies. A total of 80% of North American studies utilized RS indices. Over half of the studies used RS to identify environmental and geophysical changes caused by WDS. The temporal trend reveals a general increase in the total number of studies, particularly for SSWD and WDSA. This study calls for more research on the use of satellite-based RS in WDS applications.

Author Contributions: N.K.: Conceptualization, Investigation, Software, Writing—Original Draft. K.T.W.N.: Conceptualization, Methodology, Formal analysis, Project administration. T.S.M.: Formal analysis, Writing—Review and Editing. K.K.A.: Formal analysis, Writing—Review and Editing. S.K.: Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: All data generated or analyzed during this study are included in this article.

Conflicts of Interest: The authors declare that they have no competing interests. The authors have no relevant financial or non-financial interests to disclose.

Abbreviations

ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer.
AVIRIS-NG	Airborne Visible Infrared Imaging Spectrometer—Next Generation.
CERES	Clouds and the Earth's Radiant Energy System.
GIS	Geographical Information System.
LST	Land Surface Temperature.
MISR	Multi-angle Imaging SpectroRadiometer.
MODIS	Moderate Resolution Imaging Spectroradiometer.
MOPITT	Measurement of Pollution in The Troposphere.
NDVI	Normalized Difference Vegetation Index.
RS	Remote Sensing.
SAVI	Soil Adjusted Vegetation Index.
SSWD	Suitable Site detection for Waste Disposal site.
SWM	Solid Waste Management.
UAV	Unmanned Aerial Vehicle.
WDS	Waste Disposal Site.
WDSA	Waste-Disposal-Site-Induced Anomaly detection.
WDSD	Waste Disposal Site Detection.

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