

WP 1 Development of cross-border participative strategies in waste reduction Certification

D.1.9.1 Methodology for identifying, marking and mapping locations where waste accumulates the most

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Executive Summary

This document provides a comprehensive overview of the methodological framework for Wastereduce Activity 1.9.1 within Workpackage 1, which focuses on identifying, marking, and mapping waste accumulation in pilot-protected and Natura 2000 areas. The primary goal of this activity is to apply advanced remote sensing technologies and analytical methods to effectively detect and manage waste in these ecologically sensitive regions. The introduction section details the five selected pilot sites for the study: Akvatorij zapadne Istre, Ušće Raše, Ušće Mirne, Uvala Sakarun, and Grave e Zone umide della Brenta. It describes the format and storage protocols for the data collected, ensuring consistency and accessibility. Additionally, the document includes a repository for all consulted documentation, providing a central location for reference materials.

The report reviews various methods for remote waste identification, highlighting single-parameter and multiple-parameter analysis techniques. It also provides an overview of available satellite resources and datasets, emphasizing the technologies and data essential for the project's success.

The methodologies to be applied in the Wastereduce project encompass a range of techniques. Visual interpretation will leverage expert analysis of satellite images to identify waste locations. Descriptive indices extraction will involve calculating metrics such as Land Surface Temperature (LST), vegetation indices, domain-specific indices, and spectral signatures to detect waste. Multi-factor analysis will integrate various geospatial and environmental variables to create probability maps that highlight potential waste sites. Features extraction and classification will focus on extracting and analyzing spatial and spectral features from images to enhance detection capabilities. Traditional computer vision techniques will apply object-based and pixel-based classification methods for waste identification, while deep learning approaches will utilize advanced neural network architectures like CNNs and U-Net for improved accuracy in image classification and semantic segmentation.

In conclusion, the document emphasizes that the selection and application of these methodologies will depend on the availability of high-resolution satellite imagery, thermal and vegetation indices, and other relevant data. The methods chosen will be based on their reliability and the project's time constraints, ensuring a thorough and effective approach to mapping and managing waste accumulation in the designated pilot areas.

1. Introduction

Solid waste sites could produce hazardous materials that cause soil contamination, which is a contributor to point-source pollution. Moreover, the accompanied harmful substances would also be transferred to the water bodies (i.e. rivers, lakes, reservoirs) during the precipitation process, leading to non-point source pollution, which will degrade the quality of cultivated land and endanger the safety of drinking water sources. It is of great significance to monitor and delineate the spatial distribution of the solid waste sites, which could provide geo-referenced data for environmental protection actions.

Activity 1.9.1 in WP1, titled “Identifying, marking, and mapping locations in pilot-protected and Natura 2000 areas where waste is systematically accumulated”, aims of this action are the two-folds: 1) to detect solid waste sites with high accuracy proposing a novel deep learning model for solid waste mapping from very high resolution remote sensing imagery and 2) to apply a geographic information system (GIS) based algorithm for optimal location and number of storage bins within selected Natura 2000 sites.

1.1 Selected Pilot Sites

Before beginning the analysis phase of the methodologies to be used for the objectives of Activity 1.9, it was essential to define the areas that will constitute the pilot sites, all of which belong to the Natura 2000 Network. As a general definition, the sites in the Natura 2000 network are designated under the 'Nature Directives', i.e. the Birds and the Habitats Directives. The target of both directives (specifically set out within the Habitats Directive and echoed in the Birds Directive) is to ensure the long-term sustainability of the habitats and species they have been set up to protect. The European Union is one of the Contracting Parties to the Bern Convention on the Conservation of European Wildlife and Natural Habitats. The Habitats Directive and subsequently the Natura 2000 network were set up in order to fulfil the EU's obligations to the Convention. Natura 2000 sites are therefore considered as the contribution from EU Member States to the Pan-European Emerald Network of the Bern Convention.

The Birds Directive established an EU-wide protection regime for all bird species naturally occurring in the EU. It included classification by Member States of *Special Protection Areas (SPA)* for 194 particularly threatened bird species and for

all migratory birds. This approach was extended through the Habitats Directive, which also provided for the establishment of a representative system of legally protected areas throughout the EU. These areas are named *Sites of Community Importance (SCI)* and aim for the conservation of the 233 habitat types listed in Annex I of the Directive and the 900 plus species listed in Annex II. SCIs must also be designated as *Special Areas of Conservation (SAC)* as soon as possible and within six years at most. SPAs and SCIs/SACs together make up the Natura 2000 network.

The following sections describe the pilot areas selected by the project partners, which will be the focus of study and testing, both for remote methodologies related to waste analysis and for the specific studies outlined in the methodological report of Activity 1.8, "Conducting in-depth interviews, surveys, and sessions of behavioral observation." The table below lists the official names of the pilot sites, their extent, and the type to which they belong, according to the Natura 2000 nomenclature. In the subsequent paragraphs, each site is identified by its specific characteristics.

Table 1.1 – List of pilot sites selected for the Wastereduce project and belonging to the Natura 2000 Network in Italy and Croatia. The table, in addition to the code and official name, also includes a link to the website with detailed information about each area.

Site Code	Site Name	Country	Site Type	Official site
HR1000032	Akvatorij zapadne Istre	HR	Bird Directive	https://eunis.eea.europa.eu/sites/HR1000032
HR3000432	Ušće Raše	HR	Habitat Directive	https://eunis.eea.europa.eu/sites/HR3000432
HR3000433	Ušće Mirne	HR	Habitat Directive	https://eunis.eea.europa.eu/sites/HR3000433
HR3000069	Uvala Sakarun	HR	Habitat Directive	https://eunis.eea.europa.eu/sites/HR3000069
IT3260018	Grave e Zone umide della Brenta	IT	Habitat and Bird Directive	https://eunis.eea.europa.eu/sites/IT3260018

1.1.1 Akvatorij zapadne Istre

The Natura 2000 site "Akvatorij zapadne Istre" (code HR1000032, Figure 1.1) is a crucial marine area located in the Jadranska Hrvatska region of Croatia, encompassing 155 square kilometers, 93% of which is marine. Classified as a Special Protection Area (SPA) under the Birds Directive since July 2013, this site plays a significant role in the conservation of avian species within the Mediterranean and Marine Mediterranean biogeographical regions. It provides protection for six bird species listed in the Nature Directives, including the Kingfisher (*Alcedo atthis*), Black-throated Diver (*Gavia arctica*), Red-throated Diver (*Gavia stellata*), Mediterranean subspecies of Shag (*Phalacrocorax aristotelis desmarestii*), Common Tern (*Sterna hirundo*), and Sandwich Tern (*Sterna sandvicensis*). Despite its extensive marine environment, the site does not protect any specific habitat types under the Habitats Directive.

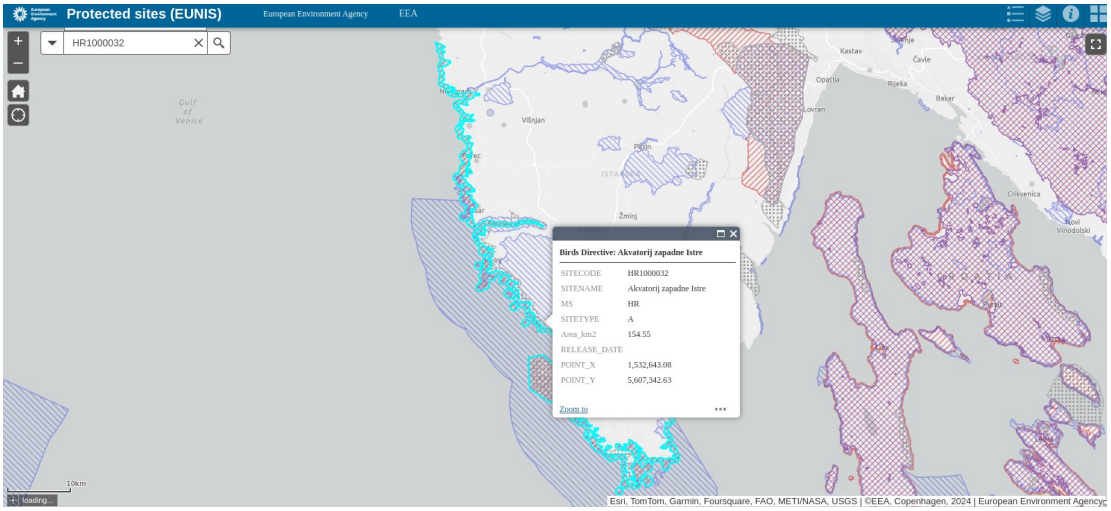


Figure 1.1 - Location of the pilot site "Akvatorij zapadne Istre" Croatia. Image downloaded from https://maps.eea.europa.eu/

1.1.2 Ušće Raše

The Natura 2000 site "Ušće Raše" (code HR3000432, Figure 1.2) is a significant conservation area located in the Jadranska Hrvatska region of Croatia. With a surface area of 44.47 hectares, 86% of which is marine, the site has been protected under the Habitats Directive since July 2013. Situated in the Mediterranean and Marine Mediterranean biogeographical regions, "Ušće Raše" safeguards one species listed in the Nature Directives, the Painzza's Goby (*Knipowitschia panizzae*), as well as two habitat types: sandbanks that are slightly covered by sea water all the time (habitat code 1110) and estuaries (habitat code

1130). The site was proposed as a Site of Community Importance (SCI) in July 2013 and confirmed in December 2014.

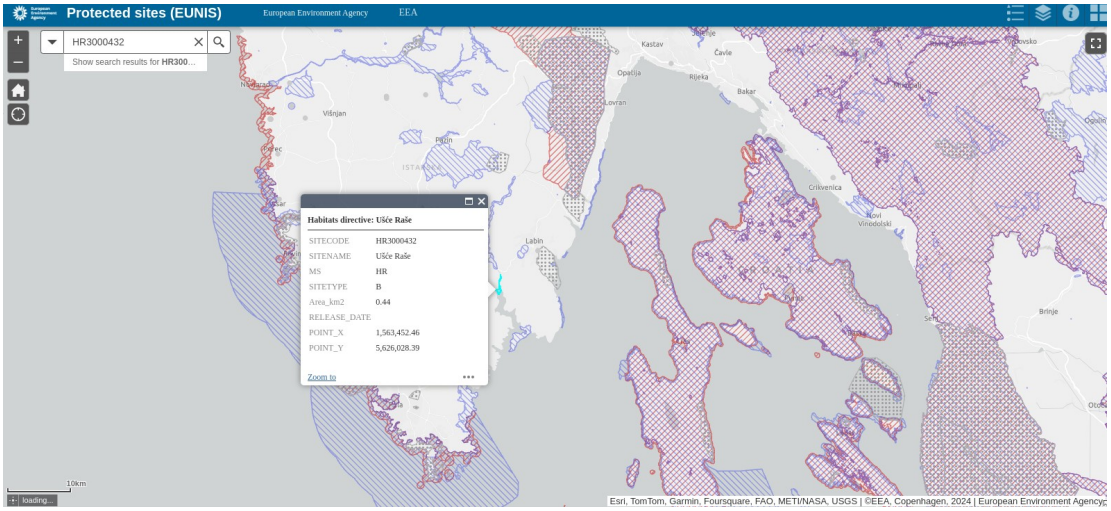


Figure 1.2 - Location of the pilot site "Ušće Raše" Croatia. Image downloaded from https://maps.eea.europa.eu/

1.1.3 Ušće Mirne

The Natura 2000 site "Ušće Mirne" (code HR3000433, Figure 1.3) is a protected area located in the Jadranska Hrvatska region of Croatia, covering a surface area of 115.34 hectares, with 50% of the area being marine. Since July 2013, it has been safeguarded under the Habitats Directive. The site is situated in the Mediterranean and Marine Mediterranean biogeographical regions and is noted for protecting three habitat types: sandbanks slightly covered by seawater (habitat code 1110), estuaries (habitat code 1130), and Mediterranean and thermo-Atlantic halophilous scrubs (habitat code 1420). While "Ušće Mirne" does not protect any specific species under the Nature Directives, its habitats are of significant ecological value. The site was proposed as a Site of Community Importance (SCI) in July 2013 and was confirmed in December 2014.

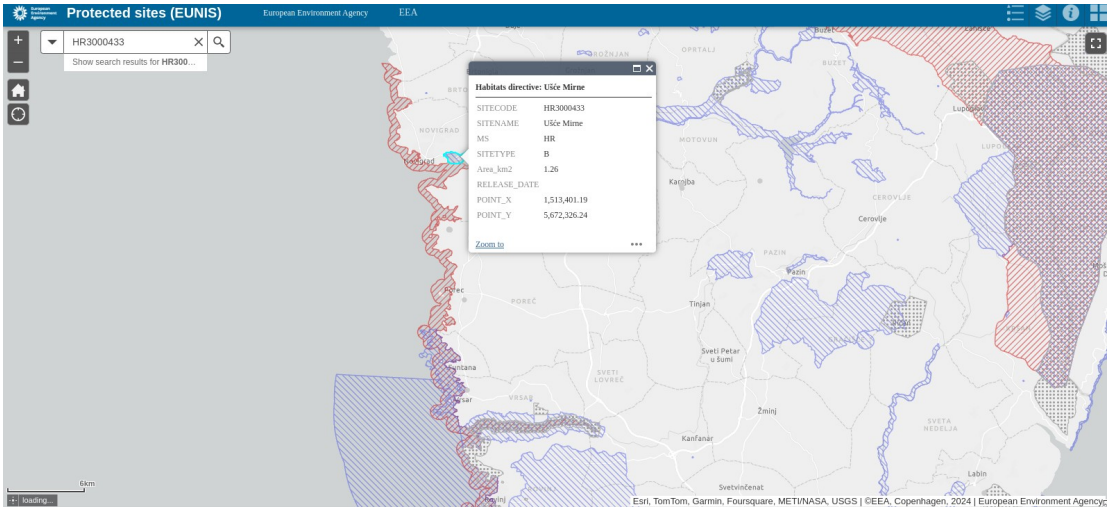


Figure 1.3 - Location of the pilot site "Ušće Mirne" Croatia. Image downloaded from https://maps.eea.europa.eu/

1.1.4 Uvala Sakarun

The Natura 2000 site "Uvala Sakarun" (code HR3000069, Figure 1.4) is a marine protected area in Croatia, covering an area of 438.54 hectares, entirely marine. Classified under the Habitats Directive since July 2013, this site is located within the Marine Mediterranean biogeographical region. "Uvala Sakarun" is recognized for safeguarding two important habitat types: Posidonia beds (*Posidonion oceanicae*, habitat code 1120) and reefs (habitat code 1170). While the site does not protect any specific species under the Nature Directives, its habitats are of significant ecological importance. The site was proposed as a Site of Community Importance (SCI) in July 2013 and confirmed in December 2014.

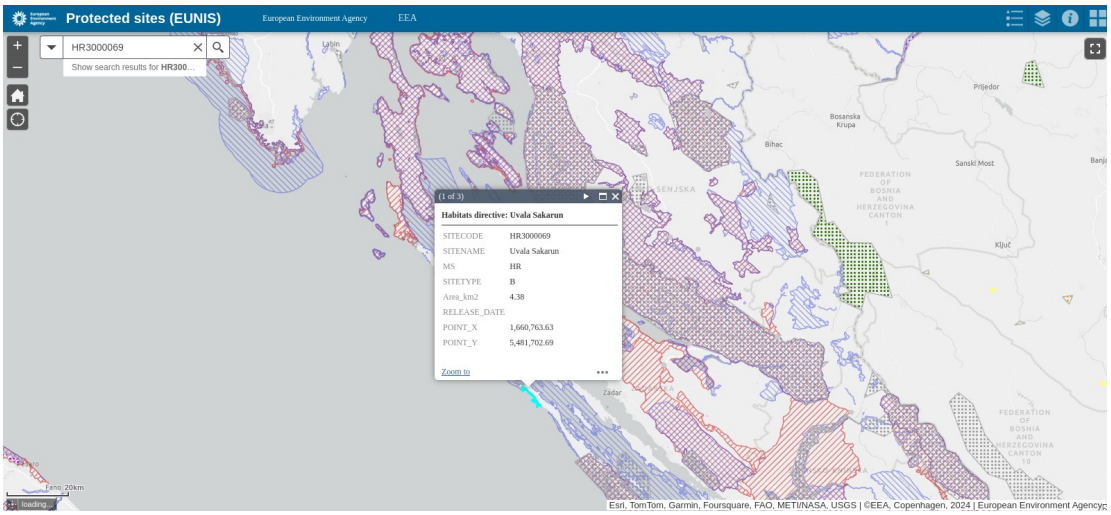


Figure 1.4 - Location of the pilot site "Uvala Sakarum" Croatia. Image downloaded from https://maps.eea.europa.eu/

1.1.5 Grave e Zone umide della Brenta

The Natura 2000 site "Grave e Zone umide della Brenta" (code IT3260018, Figure 1.5) is a significant conservation area located in the Veneto region of Italy, within the Continental biogeographical region. Covering an area of 3,848 hectares, this site has been protected under both the Birds Directive and the Habitats Directive since September 1995. It serves as a vital habitat for 55 species listed in the Nature Directives, including amphibians like the Italian agile frog (*Rana latastei*), various bird species such as the Kingfisher (*Alcedo atthis*) and Grey Heron (*Ardea cinerea*), as well as fishes, invertebrates, mammals, and reptiles. The site also protects five important habitat types, including oligotrophic to mesotrophic standing waters, alpine rivers with ligneous vegetation, and alluvial forests with *Alnus glutinosa* and *Fraxinus excelsior*. The "Grave e Zone umide della Brenta" was classified as a Special Protection Area (SPA) in August 2003 and was designated as a Special Area of Conservation (SAC) in July 2018.

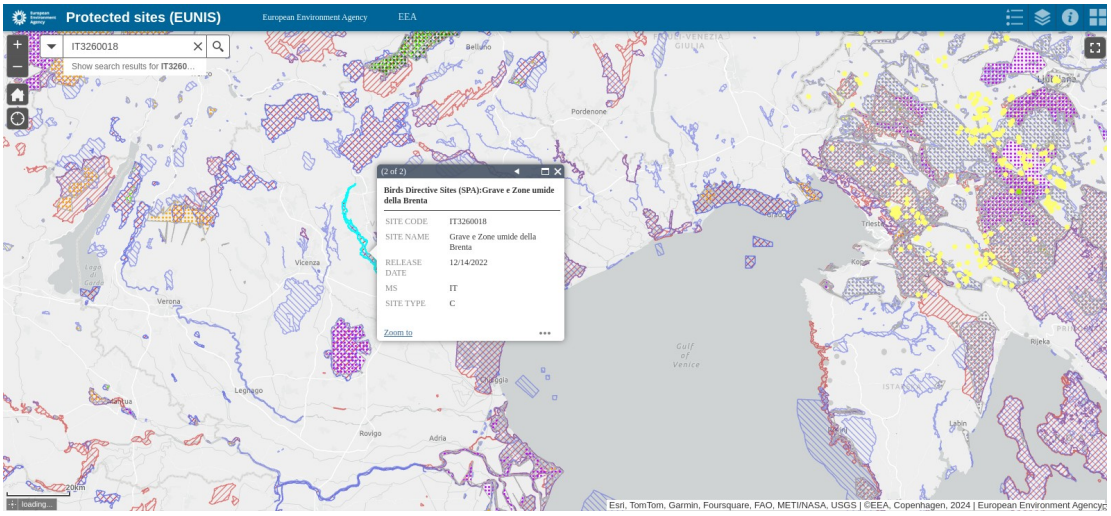


Figure 1.5 - Location of the pilot site "Grave e Zone umide della Brenta" Italy. Image downloaded from https://maps.eea.europa.eu/

Regarding the site "Grave e Zone umide della Brenta" it was decided to focus the project actions on the area of the site located within the Veneto municipalities of Cittadella, Carmignano di Brenta, Grantorto, Fontaniva, San Giorgio in Bosco, Campo San Martino, Curtarolo, Vigodarzere, Limena, and Piazzola sul Brenta. This decision reduces the total area of the site considered as the pilot area from 3,848 hectares to 3,187 hectares. This choice is justified by the fact that these municipalities are where the activities of the partner ETRA take place, and where the activities of action 1.8 will therefore be carried out. Figure 1.6 shows the area of the "Grave e Zone umide della Brenta" site selected as the pilot area.

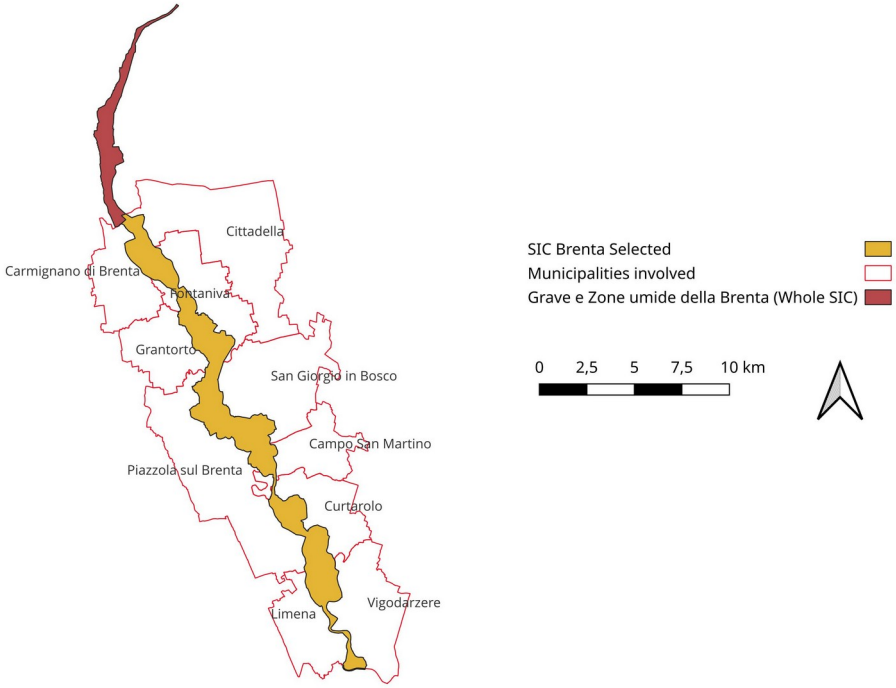


Figure 1.6 - Location of the pilot site "Grave e Zone umide della Brenta" Italy. Image downloaded from https://maps.eea.europa.eu/

1.2 Data Format and data storage

To ensure robust data management and alignment with best practices in geospatial analysis, the Wastereduce project has adopted several critical standards for data storage and formatting. Specifically, all spatial datasets, including shapefiles and raster files, will be referenced using the EPSG:32633 coordinate system (https://www.klokantech.com/). This system corresponds to UTM Zone 33N under the WGS 84 datum, providing a consistent and widely recognized framework for accurate geospatial positioning. The choice of EPSG:32633 is particularly suited for the geographic scope of the project, covering areas within this UTM zone with high precision.

In terms of data organization, all geospatial layers will be encapsulated within a Geopackage file format. Geopackage is an open-source, platform-independent format that supports a wide range of data types, including vector features, tile matrices (for raster data), and attribute tables. The use of Geopackage not only ensures that all spatial data is stored in a single, compact, and highly portable file but also supports transactional capabilities, which are vital for maintaining data integrity during editing processes. Moreover, as a non-proprietary format,

Geopackage facilitates interoperability between different software platforms and ensures long-term accessibility without the risk of vendor lock-in. The project's commitment to open-source principles is further demonstrated by the exclusive use of QGIS for all geospatial data handling. QGIS, an open-source Geographic Information System (GIS), provides a comprehensive suite of tools for spatial analysis, mapping, and data visualization. Its compatibility with a variety of data formats, including Geopackage, and its ability to handle complex geospatial operations make it an ideal choice for the project's needs. Moreover, QGIS supports the integration of open data sources, which will be utilized wherever possible to enhance the project's transparency and contribute to the broader open data movement. By adhering to these standards, the project not only ensures a high level of technical rigor but also aligns with broader goals of sustainability, openness, and collaboration. The careful selection of data formats and tools will facilitate smooth data sharing, enhance reproducibility of results, and support future uses of the data by the community or other projects. This approach underscores the project's commitment to leveraging open-source software and open data, thereby promoting broader accessibility and contributing to the development of shared geospatial knowledge.

In addition to the data formats and standards previously discussed, the project will adopt the Dublin Core Metadata Standard (DCMS) ("Dublin Core; Metadata Element Set, Version 1.1") for the creation and management of metadata associated with the geospatial layers produced. The Dublin Core is a widely recognized standard that provides a simple and flexible framework for describing a wide range of digital resources. It consists of a set of 15 core elements, such as Title, Creator, Subject, and Date, which are used to describe the content, context, and structure of the data. This standard is particularly suitable for geospatial data because it ensures that the metadata is interoperable, easily accessible, and understandable by both humans and machines. Once the geospatial layers have been created and stored in the Geopackage format, the corresponding metadata will be meticulously generated according to the Dublin Core standard. This metadata will capture essential information about the spatial data, including its source, accuracy, resolution, and any processing steps applied. By adhering to the Dublin Core standard, the project ensures that all data is accompanied by comprehensive and consistent metadata, facilitating data sharing, reuse, and long-term preservation. The adoption of the Dublin Core standard also aligns with the project's commitment to using open-source tools and open data whenever possible. Metadata created according to this standard can be easily integrated into various geospatial

platforms and databases, further enhancing the interoperability and discoverability of the data within the broader research and environmental management communities.

To ensure the successful implementation of the aforementioned data formats and standards, the University of Trieste (UniTs) organized an online workshop on July 11th, 2024. During this session, all the partners have been provided with a concise online introduction to the use of Geopackages within the QGIS system.

1.3 Repository for Consulted Documentation

The foundation of report for the Activity 1.9.1 lies in the detailed description and analysis of methodologies for remotely identifying waste types, understanding where waste tends to accumulate, and monitoring its distribution over time. Given the complexity and importance of these tasks, a thorough and systematic review of the scientific literature was conducted to ensure that the most up-to-date and effective methods are employed in the project. This review process involved an extensive search through the Scopus database (www.scopus.com), one of the most comprehensive and widely-used scientific databases. Through this platform, we accessed a wide array of peer-reviewed papers, articles, and other relevant publications that address various aspects of remote sensing, waste management, and environmental monitoring. The methodologies and findings from these sources were critically analyzed, compared, and synthesized into a coherent framework that will guide the identification and monitoring processes within the WASTEREDUCE project. Recognizing the need for continuous access to this knowledge base, as well as the potential for future developments in the field, all the consulted documentation has been organized and stored in an online repository. This repository is managed through Zotero (www.zotero.org), an open-source reference management tool known for its robust features in citation management, collaborative research, and data sharing. Zotero not only provides an efficient way to store and categorize these documents but also ensures that all project partners have real-time access to the latest research findings. To facilitate ongoing collaboration and ensure that the WASTEREDUCE project remains aligned with emerging methodologies, the repository will be regularly updated as new literature is published. This will allow the project to adapt to any advancements in remote waste identification and environmental monitoring techniques, thereby maintaining the relevance and accuracy of the methods applied. The current repository, which houses all the consulted and synthesized documentation to date, is freely accessible to all

project partners via the following link: www.zotero.org/groups/5621811/wastereduce_methodology . This resource is intended to be a living database, continually enriched with new information, and serves as a cornerstone for the collaborative efforts of the WASTEREDUCE project. By ensuring that all partners have easy and open access to the most current and relevant research, we can collectively advance our understanding and implementation of effective waste management strategies across the pilot sites.

2. A review of methods for remote identification of waste

The identification, tracking, and management of waste are increasingly pressing challenges in environmental science, particularly in the context of global efforts to reduce pollution and mitigate climate change. Traditional methods of waste identification and monitoring, which often involve ground surveys and manual data collection, have proven to be resource-intensive and limited in scope (Olawade et al. 2024). As a result, there has been a growing interest in the development and application of remote sensing technologies to address these challenges more efficiently and effectively. Remote sensing, which involves the acquisition of information about an object or phenomenon without making physical contact, offers a range of tools and techniques that can be employed to detect and monitor waste over large areas and across different time scales (Janga et al. 2023). These methods leverage various types of sensors—optical, thermal, radar, and multispectral—that are deployed on platforms such as satellites, drones, and aircraft. The data collected through these sensors can then be analyzed to identify waste materials, track their distribution, and monitor changes over time (Figure 2.1).

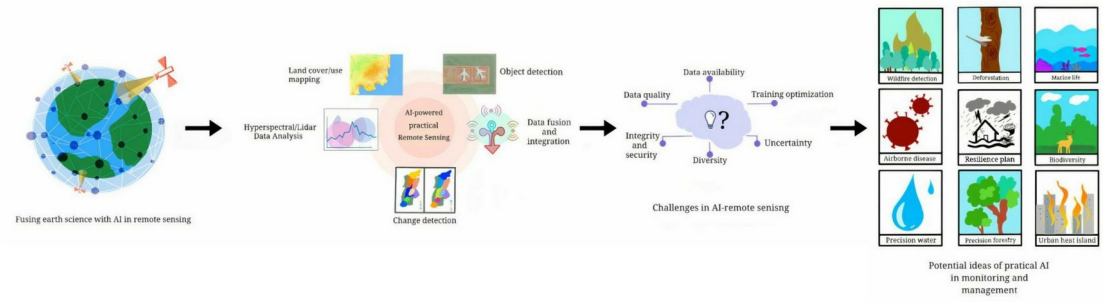


Figure 2.1 – A simplified framework for data integration combining AI, remote sensing and potential application (including waste identification). Image from Janga et al. 2023.

One of the key advantages of remote sensing in waste management is its ability to cover vast and often inaccessible areas, providing continuous and comprehensive data that would be impossible to obtain through traditional methods alone. This capability is particularly valuable in identifying illegal dumping sites, monitoring landfill usage, and assessing the impact of waste on natural ecosystems (Papale et al. 2023; Cicala et al. 2024). Moreover, the integration of remote sensing with geographic information systems (GIS) allows for sophisticated spatial analysis, enabling the correlation of waste distribution with other environmental and socio-economic factors (Nizamani et al. 2024).

Several pioneering projects have already demonstrated the potential of remote sensing for waste identification. For example, the European Space Agency's (ESA) Copernicus program has used satellite imagery to monitor waste management practices and identify illegal dumpsites across Europe (The European Space Agency 2024). Similarly, the Plastic Tide Project has employed drone-based imaging to detect and quantify plastic waste on beaches and coastal areas, contributing valuable data to global efforts aimed at reducing marine pollution (Schmaltz et al. 2020). The development of machine learning and artificial intelligence (AI) techniques has further enhanced the capabilities of remote sensing in waste identification. By training algorithms on large datasets, researchers can now automatically detect and classify different types of waste materials with high accuracy. These advancements have opened new possibilities for real-time monitoring and rapid response to waste-related environmental threats (Janga et al. 2023; Wu et al. 2023). However, despite the significant progress made in this field, there remain challenges and limitations that must be addressed. These include the need for higher resolution data to accurately identify small waste objects, the development of standardized protocols for data collection and analysis, and the integration of remote sensing data with ground-based observations to improve validation and reliability. This chapter aims to provide a comprehensive review of the current methods for remote identification of waste, drawing on the latest research and technological developments in the field. By synthesizing the findings from a wide range of studies, this review will offer insights into the most effective techniques for waste detection, the challenges associated with their implementation, and the future directions for research and innovation in this critical area. As the Wastereduce project progresses, the methodologies outlined in this review will serve as a foundation for the remote monitoring and management strategies employed in the pilot sites, ensuring that the project remains at the forefront of environmental sustainability efforts.

2.1 Literature Review on Remote Identification of Waste

Over the past several decades, the rapid increase in global population, industrial activity, and urbanization has led to a significant surge in waste production (Hannan et al. 2015). The challenges posed by this increase in waste are exacerbated by improper waste management practices, which have dire consequences for human health and the environment. Issues such as soil, water, and air contamination are direct results of inadequate waste disposal methods

(Giusti 2009; Khan et al. 2022). Monitoring waste-related impacts is crucial, but traditional in situ methods are often expensive, time-consuming, and logistically challenging, especially when dealing with illegal dumping sites that are unmonitored and can rapidly develop in remote locations (Iacoboaea & Petrescu 2013; Glanville & Chang 2015). In response to these challenges, remote sensing (RS) has emerged as a powerful tool for waste site detection and monitoring. RS provides cost-effective solutions for acquiring valuable data that can be used to assess the environmental impacts of waste disposal sites. Early applications of RS in landfill monitoring integrated geographic information systems (GIS) with aerial and satellite data to enhance solid waste management. Over time, the use of satellite technology has become increasingly prevalent due to its broad coverage and the ability to consistently monitor large areas without the logistical complexities associated with aerial surveys. The potential of satellite RS for monitoring waste disposal sites was first highlighted in a 1973 study (Wezernak & Thomson 1973), which demonstrated the utility of the Earth Resources Technology Satellite (ERTS-1) equipped with a multi-spectral scanner sensor for observing large-scale events such as ocean dumping. This study marked one of the earliest instances where spacecraft data were used to monitor a large ocean dump area near the New York Metropolitan area, showcasing the capabilities of satellite RS for environmental monitoring on a significant scale. Subsequent research further explored the integration of RS data with GIS for waste management. For instance, a study (Jensen & Christensen 1986) demonstrated the application of GIS and RS data, specifically using aerial photography and Landsat multispectral scanner data, to identify suitable sites for industrial waste storage. This approach allowed for the efficient gathering of land cover and land use information necessary for site selection. In more recent years, the use of high-resolution satellite imagery has advanced the detection and monitoring of illegal landfills. (Biotto et al. 2009), for instance, utilized Ikonos data to update and correct regional infrastructure maps, thereby identifying unauthorized landfill sites. This application highlighted the importance of accurate spatial data in the detection of illegal waste disposal activities. Another innovative approach was developed by (Lucendo-Monedero et al. 2015), who employed a logistic regression model to detect areas with illegal landfills in Andalusia. By analyzing geographical and behavioral variables, they were able to predict potential illegal waste disposal sites, demonstrating the effectiveness of combining RS data with statistical models for environmental monitoring.

The methodologies for detecting and analyzing waste sites using RS have evolved significantly, with multispectral sensors onboard satellites playing a

central role. These sensors capture data across various wavelengths of the electromagnetic spectrum, enabling the analysis of spectral signatures associated with different types of waste. Three main aspects have been identified for detecting waste sites using RS images (Notarnicola et al. 2004):

1) thermal anomalies;

2) vegetation stress;

3) specific spectral signatures.

These indicators provide critical information for identifying and monitoring waste disposal sites, particularly when integrated with GIS and ground-based data. Hereafter, structuring this review, the classification proposed by (Papale et al. 2023), as illustrated in Figure 2.2. was adopted. This classification divides the available methods for waste identification into two main categories: single-parameter-based analysis and multiple-parameter-based analysis.

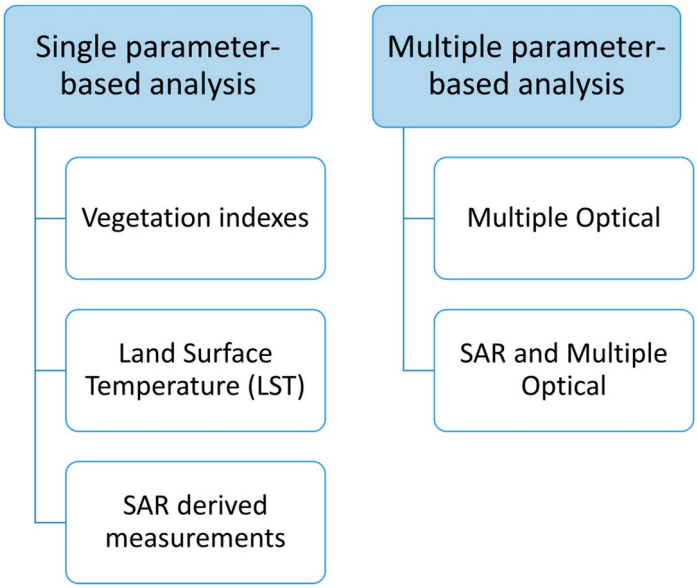


Figure 2.2 – Classification of methodologies available for waste identification from RS approaches following Papale et al. (2023).

The single-parameter-based analysis includes studies that distinctly used information from a specific portion of the electromagnetic spectrum, while the latter includes studies that combined such information

2.1.1 Single-Parameter-Based Analysis

The single-parameter-based analysis can be divided into different sub-classes based on the type of data used from the electromagnetic spectrum. These are:

- Vegetation-Indexes-Based Analysis: many published approaches involve using spectral vegetation indexes derived from satellite and ground-based data to identify and monitor landfill sites and site where waste are accumulated. This approach leverages various vegetation indexes obtained through multispectral sensors to detect changes associated with waste disposal sites. For instance, (Manzo et al. 2017) proposed a method that utilized very high-resolution multispectral satellite data from Pleiades (https://earth.esa.int/eogateway/missions/pleiades) and WorldView2 sensors (https://earth.esa.int/eogateway/missions/worldview-2), along with aerial orthophotos, to identify points of interest for monitoring areas where waste accumulate. The study analyzed two key spectral indexes: the Normalized Difference Vegetation Index (NDVI) and the Global Environmental Monitoring Index (GEMI). Both indexes are sensitive to reflectance in the visible to near-infrared range, but GEMI is less affected by atmospheric conditions and sensor types than NDVI, though it is more sensitive to bare soil variations. This multi-temporal change detection approach significantly enhanced in situ geomatic surveys, providing valuable insights into detecting critical points and major changes in the study area in Calabria Region, Italy. Another relevant study using vegetation spectral indices (Silvestri & Omri 2008) examined the relationship between dump-induced contamination and vegetation stress to identify uncontrolled landfills, with a focus on the watershed area of the Venice lagoon, Italy. This research integrated GIS and remote sensing data from the multispectral, pan-sharpened IKONOS sensor with a spatial resolution of 1 meter. The analysis aimed to identify stressed vegetation associated with landfills, using machine learning algorithms trained with local authority data and combined with visual interpretation of aerial photographs and GIS information such as road networks and population density. The findings underscored vegetation stress as a reliable indicator for illegal landfill detection. The study by (Mahmood et al. 2019) compared several multispectral vegetation indexes, including NDVI, the Soil-Adjusted Vegetation Index (SAVI), and the Modified Soil-Adjusted Vegetation Index (MSAVI), to assess environmental risks from open dumps in Pakistan. This analysis, using Landsat 8 data, revealed that before the onset of dumping, no significant vegetation health variations were observed. However, after dumping commenced, vegetation stress was found to increase as proximity to the landfill decreased, with MSAVI proving to be the most effective index for detecting such stress.

(Mahmood et al. 2017) combined GIS and remote sensing for risk assessment of illegal waste dumping. The study developed an algorithmic criterion to evaluate hazardous effects from different solid waste, using very high-resolution data from QuickBird to generate land cover maps. By integrating multispectral images from the FORMOSAT-2 satellite, the study improved risk assessment mapping through spectral feature integration, although higher spectral resolution imagery might help reduce misclassification between waste materials and bare soil.

A change detection method developed by (Massarelli 2018) aimed to distinguish waste burial sites using Landsat 7 and Landsat 8 images processed with GRASS GIS (https://grass.osgeo.org/). This method included unsupervised classification and tasseled cap transformation to identify the most changed areas, using a "Greenness Empirically Normalization Index" derived from the greenness vegetation index. Ground truth validation through high-resolution archive images confirmed the method's effectiveness. In a different context, (Aslam et al. 2022) proposed a method for identifying and ranking landfill sites in Faisalabad, Pakistan, using RS data and GIS. This study employed NDVI, NDWI, and the Normalized Difference Built-Up Index (NDBI) derived from Landsat 8, combined with physical factors like water bodies, roads, and population density, to rank potential sites for landfill development. Additionally, (Mallick 2021) utilized NDVI and land use/land cover maps with Sentinel-2 data to identify and rank possible dumping sites in Saudi Arabia, integrating these with other geophysical and spatial information to select suitable waste disposal locations.

- Land-Surface-Temperature-Based Analysis: these approaches focus on utilizing land surface temperature (LST) data derived from the thermal infrared channels of Landsat satellites for waste disposal site analysis. This approach has proven effective in various studies, highlighting the utility of LST in identifying and monitoring even illegal waste accumulation activities. Specifically, the study by (Cicala et al. 2024) demonstrated the effectiveness of a multitemporal LST analysis for landfill monitoring. Using Landsat Thematic Mapper and Enhanced Thematic Mapper Plus images, this research covered a temporal range of 10 years, with data collected during both summer and winter seasons. The study aimed to identify waste-dumping regions by analyzing LST variations over time. Results indicated that LST is particularly effective for pinpointing waste locations, with summer acquisitions showing more pronounced heat flux, thus providing clearer indications of waste-dumping areas. Landsat data were also utilized to develop a methodology for detecting landfill fires by correlating temperature

anomalies with known landfill sites (Nazari et al. 2020). The study used LST maps derived from Landsat 5 and Landsat 8 over a 17-year period. This approach effectively linked temperature anomalies to landfill fires, providing a valuable tool for monitoring and managing landfill fires through thermal infrared data. It has also demonstrated the relationship between LST and the volume of solid waste buried in landfills (Abu Qdais & Shatnawi 2019). A neural network algorithm, incorporating landfill-site-specific information along with meteorological parameters to estimate LST, was used. The findings highlighted a significant correlation between LST and the amount of buried waste, enhancing the understanding of temperature variations in relation to landfill waste volumes. Finally, it has been demonstrated the pronounced temperature contrast between landfills and their surroundings, reinforcing the utility of LST in landfill monitoring (Le Hung Trinh et al. 2021).

- SAR-based Analysis: SAR-based analysis involves the use of synthetic aperture radar (SAR) data to monitor and assess waste accumulation sites. This method leverages radar imaging to provide valuable information on waste disposal sites, landfill characteristics, waste volume and possible site deformation. Among the other studies, (Ali et al. 2016) employed a single Radarsat-1 C-band SAR acquisition to monitor multiple municipal solid waste (MSW) sites in Riyadh, Saudi Arabia. They processed a Radarsat-1 backscattering image (in F2 mode) and utilized stereo-SAR techniques to generate a digital elevation model (DEM) for orthorectification. Image segmentation and supervised classification were performed using PCI software version 10 with ground-truth samples. This study confirmed the utility of SAR imagery and digital image processing techniques for effective solid waste site monitoring. The use of SAR interferometry provides enhanced insights into landfill characteristics by analyzing changes in the radar backscatter signal over time. For instance, (Karathanassi et al. 2012) monitored waste disposal volume changes in a landfill in Athens by employing two pairs of ENVISAT ASAR images. The SAR interferometry technique was used to create two DEMs, which were then subtracted to derive elevation changes. This method enabled a detailed examination of waste volume variations through elevation profiles. The interferometric SAR (InSAR) technique, in combination with unmanned aerial vehicle (UAV) photogrammetry and ground measurements, has been applied to assess landfill deformation and related risks (Zhang et al. 2021): Sentinel-1 data was used to monitor the Tianziling landfill in China, one of the largest engineered sanitary landfills in the region. The study integrated SAR data with UAV and ground-based measurements to evaluate deformation,

identifying potential subsidence areas for risk assessment. The results indicated that the approach could detect deformations ranging from millimeters to meters, which is crucial for assessing landfill stability. Finally, differential InSAR techniques were utilized to monitor landfill settlements at the Montegrosso-Pallareta landfill in Italy (Milillo et al. 2015). Multi-temporal COSMO-SkyMed interferometric data provided millimetric accuracy in monitoring low-magnitude landfill settlements.

2.1.2 Multiple-Parameter-Based Analysis

This methods combine satellite-sensor-derived information acquired at the VIS-NIR-SWIR, TIR, and microwave parts of the electromagnetic spectrum, respectively. In the specialized literature, two main categories can be identified (Papale et al. 2023): multiple-optical-parameters based analysis and the combination of SAR and multiple-optical-parameters based analysis.

- Multiple-Optical-Parameters-Based Analysis

A number of studies have explored the integration of temperature information with multispectral indexes to enhance the analysis of waste accumulation sites. These approaches combine land surface temperature (LST) data with various optical parameters, providing a more comprehensive view of landfill conditions and their environmental impacts. For instance, the study by (Yan et al. 2014) incorporated NDVI visual analysis alongside LST measurements. This research employed Landsat Thematic Mapper data to derive both LST and NDVI images from 81 acquisitions across different seasons. The results demonstrated that LST at waste accumulation sites is consistently higher compared to surrounding vegetation and air temperature, with this difference being most pronounced during the spring and summer. Similarly, (Mahmood et al. 2019) integrated LST into their analysis of vegetation indexes to evaluate the bio-thermal impact of two dumping sites in Pakistan. Using Landsat 8 data, they showed that LST decreases with increasing distance from the landfill sites, validating their earlier findings with more detailed temporal data.

In another study, Yang et al. (2021) combined remote sensing (RS) data with GIS to analyze leachate and gas emissions from landfills in Jiangsu Province, China. They employed LST, NDVI, and the clay minerals index (CMI) to assess various aspects of landfill operations. LST differences between landfills and surrounding areas were linked to biodegradation processes and gas release. NDVI served as

an indicator of leachates by correlating with soil water content, while CMI assessed the clay concentration used for containment. Landsat-7 Enhanced Thematic Mapper Plus (ETM+) imagery was utilized to compute these indexes, and the results were integrated with digital maps and regional data to perform a spatial analysis of landfill areas and their environmental conditions. (Sarp & Ozcelik 2018) explored the impact of an abandoned quarry used for uncontrolled waste disposal on groundwater, LST, surface moisture, and vegetation cover. They used Landsat 8 imagery from 2014 and 2017 to compute LST and assess changes over time. Multispectral indexes NDMI and SAVI were employed to evaluate surface moisture and vegetation impact, respectively. Pearson's correlation coefficient was used to analyze the relationships between LST, NDMI, and SAVI. The study revealed that solid waste disposal led to groundwater pollution, increased surface temperature, and reduced soil moisture. (Ganci et al. 2021) proposed a methodology to characterize waste disposal site activity by analyzing surface conditions using multispectral satellite images from Landsat (4, 5, 7, 8), EOS-Aster, Sentinel-2, and Doves-Planetscope. They derived LST, NDVI, and NDWI to assess surface temperature, vegetation state, and soil moisture. In Saskatoon, Canada, (Karimi et al. 2022) used satellite imagery and vector data to produce a probability map of illegal dump sites. They combined night-time light data from the VIIRS sensor with Landsat 8 imagery to derive LST and MSAVI indexes. The study found MSAVI to be a significant factor for detecting illegal dump sites, while LST was less effective for smaller-scale landfills. Similarly, (Karimi & Ng 2022) used LST, the enhanced vegetation index (EVI) from MODIS data, and the formaldehyde total column (HCHO) from the Aura Ozone Monitoring Instrument (OMI) to detect illegal dump sites. EVI, minimizing atmospheric and canopy background noise, proved useful for site detection, while LST and highways were important indicators. HCHO showed limited spatial sensitivity, reducing its effectiveness in this context.

- SAR- and Multi-Optical-Parameters-Based Analysis

The combination of Synthetic Aperture Radar (SAR) data with multispectral and hyperspectral optical parameters has proven to be a powerful approach for monitoring and managing solid waste deposits. This integrated method leverages the strengths of both SAR and optical remote sensing technologies, offering a more detailed and comprehensive analysis of waste accumulation sites. Using the above mentioned approach, a study in the UK (Ottavianelli et al. 2006) demonstrated the utility of integrating hyperspectral and SAR data for landfill management. SAR images from the ERS and Envisat satellites have been

analyzed to analyze backscatter and interferometric coherence, which are sensitive to structural changes induced by landfill operations. Additionally, they utilized a hyperspectral scene acquired by the Compact High-Resolution Imaging Spectrometer (CHRIS) on the PROBA-1 satellite. The hyperspectral data, used as a red-green-blue composite, proved to be more effective than conventional multispectral data in monitoring landfill activities, highlighting the added value of high-resolution hyperspectral imaging in waste management. Another study (Yonezawa 2009) explored the joint use of multispectral and SAR data to monitor waste disposal sites. The research employed ALOS PRISM, AVNIR-2, and PALSAR acquisitions to identify junkyards through visual inspection of pan-sharpened PRISM and AVNIR-2 images. The study also examined PALSAR backscatter images in HH polarization for both ascending and descending flight directions. This dual approach allowed for the detection of surface changes at waste disposal sites through visual interpretation. The study further utilized panchromatic and multispectral QuickBird data, enabling the identification of a waste-tire disposal site by distinguishing its spectral signature from the surrounding land cover types.

(Cadau et al. 2013) proposed a more integrated system for waste accumulation detection and monitoring that combines optical and SAR data. The system uses optical data (from RAPIDEYE and SPOT-5) primarily for 2D monitoring, while SAR data provide both 2D and 3D insights into landfill variations. To achieve this, the study introduced the DDI index, which combines optical-derived vegetation indexes with image textural features. Additionally, SAR data from COSMO-Skymed interferometric pairs were processed, with HH and VV pairs (from both ascending and descending paths) analyzed to extract a 3D surface elevation model. This method proved effective for detecting height variations in structures with regular geometry, where signal phase information can reveal subtle changes. Moreover, the study found that decreased coherence between different SAR image pairs often correlates with changes in the landfill's scattering mechanisms. The research also utilized night-time ASTER images, particularly thermal infrared (TIR) bands, to retrieve LST trends and detect potential thermal anomalies. (Agapiou et al. 2016) focused on the sensitivity of multispectral, hyperspectral, and SAR data in monitoring olive mill waste disposal. They employed very high resolution (VHR) multispectral data, including images from Pleiades, SPOT 6, QuickBird, WorldView-2, and GeoEye 1 satellites. The VHR images were processed to compute two indexes—NDVI and the Olive Oil Mill Waste (OOMW) index—by combining bands in the visible and VNIR parts of the spectrum. Additionally, the researchers tested a principal component

analysis (PCA) to identify optimal linear combinations of the original bands, followed by an intensity-hue-saturation (IHS) transformation for image fusion. An unsupervised classification was then performed using the ISODATA algorithm and the LSU technique to discriminate olive mill waste disposal areas. Furthermore, a COSMO-SkyMed SAR image was processed to identify disposal areas, which appeared as black targets due to the low backscatter signal, indicating a significant presence of water. Despite these efforts, when hyperspectral EO-ALI images were fused with the SAR data, the olive mill waste disposal areas were not successfully distinguished, even with the improved spatial resolution. All the cited surveys illustrate the versatility and effectiveness of combining SAR and optical data in monitoring waste disposal sites, providing critical insights into surface and structural changes, as well as the environmental impact of waste disposal sites.

2.2 Available Satellites and Resources

Over the past fifty years, Earth Observation (EO) satellite technology has made significant strides, providing increasingly detailed imagery with enhanced temporal resolution. Today, satellites are capable of capturing images with a resolution as fine as 30 centimeters, coupled with revisit times of less than a day. These advancements have greatly expanded the possibilities for environmental monitoring, including landfill detection and management. Most satellite missions offer some level of access to research projects, with several programs providing full access to historical data and quotas for current datasets. Various satellite missions are commonly employed in landfill detection research, each offering unique capabilities and products.

The WorldView series, operated by Maxar and accessible via the European Space Agency (ESA), is among the most prominent. *WorldView-1* provides panchromatic-only images with a ground sampling distance (GSD) of 50 centimeters and a revisit time of 1.7 days at 1-meter GSD or less. *WorldView-2* enhances this capability by capturing both panchromatic and 8-band multispectral imagery, including Visible Near-Infrared (VNIR) bands, with a GSD of 0.46 meters for panchromatic and 1.8 meters for multispectral images. *WorldView-3* further extends these capabilities with the addition of 8 Shortwave Infrared (SWIR) bands and 12 CAVIS (Clouds, Aerosols, Vapors, Ice, Snow) bands, providing a panchromatic GSD of 0.31 meters, VNIR GSD of 1.24 meters, SWIR GSD of 3.7 meters, and CAVIS GSD of 30 meters, all with a revisit time of less

than a day at 1-meter GSD. Although *WorldView-4*, launched in 2016, is no longer operational since 2019, its archived data remains accessible.

Another key player in this field is **GeoEye-1**, which, like the WorldView series, is optimized for large-scale projects. It captures Very High Resolution (VHR) images, with a panchromatic GSD of 0.41 meters and VNIR multispectral imagery at 1.64 meters GSD, and offers a revisit time of 1.7 days at 1-meter GSD and 3 days at 0.41-meter GSD.

The European Union's **Copernicus Programme**, developed in collaboration with the ESA, is a significant contributor to EO with open access to much of its data. *Sentinel-1*, launched in 2014, provides all-weather, day-and-night imagery through its C-band Synthetic Aperture Radar (C-SAR), with resolutions ranging from 5x5 meters to 20x40 meters and revisit times varying from less than a day to three days. *Sentinel-2*, launched in 2015, offers multispectral imaging with 13 channels in the VNIR and SWIR spectral ranges, delivering a GSD of 10 meters and a revisit time of 2 to 5 days depending on the latitude. Other Sentinel missions, such as *Sentinel-3, Sentinel-5P*, and *Sentinel-6*, focus more on atmospheric monitoring and topographic measurements, making them less relevant for landfill detection.

The **Pléiades missions**, operated by the French Space Agency (CNES) and AirBus, also play a critical role in environmental monitoring. The original Pléiades satellites provide multispectral, optical, and VNIR imagery with a panchromatic GSD of 0.5 meters and multispectral GSD of 2 meters. The more advanced *Pléiades Neo* offers even higher resolution, with 0.3-meter GSD for panchromatic and 1.2 meters for multispectral bands, with twice-daily revisit capabilities.

NASA's **LandSat program**, which began in 1972, remains a cornerstone of EO for land monitoring, agriculture, cartography, and more. Currently, *LandSat 8* and *LandSat 9* are active, with *LandSat 8* featuring the Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), providing panchromatic, optical, NIR, SWIR, and coastal aerosol images at 15 meters GSD for panchromatic and 30 meters for multispectral. *LandSat 9* continues this legacy with enhanced sensors and improved radiometric resolution.

The **SPOT satellite system**, initiated by the French Space Agency and now operated by Spot Image and AirBus, is another valuable resource, particularly for climatology, oceanography, and human activity monitoring. *SPOT 6* and *SPOT 7*, the currently active missions, provide panchromatic and VNIR imagery with a

GSD of 1.5 meters and 6 meters, respectively, and revisit times ranging from 1 to 3 days.

COSMO-SkyMed, funded by the Italian Ministries of Research and Defense, utilizes SAR sensors to produce imagery with resolutions as fine as 0.3x0.5 meters. This system is particularly useful for applications in cartography, forest protection, land management, and security, and its data is accessible through ESA for approved research projects.

Japan's **ALOS** (*Advanced Land Observing Satellite*) missions, managed by the Japan Aerospace Exploration Agency (JAXA), offer a range of applications, from cartography to disaster monitoring. *ALOS-2*, the most recent satellite in this series, operates with a Phased Array L-band Synthetic Aperture Radar (PALSAR) and a Compact InfraRed Camera (CIRC), offering resolutions from 1x3 meters to 100 meters depending on the scan size.

NASA's **Terra satellite**, part of the Earth Observing System (EOS), carries a suite of sensors, including the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), which provides high-resolution images of land and water. Terra's imaging capabilities include a GSD of 15 meters for SWIR, 30 meters for VNIR, and 90 meters for TIR with a swath width of 60 kilometers. Data from Terra is freely available, making it a valuable resource for EO applications.

PRISMA, an Earth Observation (EO) satellite developed and operated by the Italian Space Agency (ASI), is designed for medium-resolution imaging of land, vegetation, and coastal zones. Equipped with a hyperspectral sensor operating in the Visible Near-Infrared (VNIR) and Shortwave Infrared (SWIR) bands, *PRISMA* provides a 30-meter Ground Sampling Distance (GSD). Additionally, it features a panchromatic sensor with a 5-meter ground resolution. Researchers and other users can access *PRISMA's* data by registering on the ASI website.

Gaofen-2, the second high-resolution EO satellite in China's High-resolution Earth Observation System (CHEOS), was developed by the China National Space Administration (CNSA). This satellite serves applications in agriculture, disaster management, resource monitoring, and environmental protection. *Gaofen-2* is equipped with two panchromatic sensors, providing a spatial resolution of 0.8 meters, and two multispectral sensors, offering a GSD of 3.2 meters. The combination of these sensors allows for a swath width of up to 45.3 kilometers, with a revisit time ranging from 4 to 69 days, depending on the application.

Several other satellite missions have been launched for medium to high-resolution multispectral and hyperspectral imaging. These include EnMAP

(Environmental Mapping and Analysis Program), Resurs-P, PROBA-1, GHOSt, and the Aleph-1 constellation. However, as of the publication of this survey, there are no documented cases in the literature of these missions being utilized specifically for solid waste detection.

While the availability of very high-resolution imagery has significantly advanced EO capabilities, it is crucial to consider the balance between various factors such as data resolution, acquisition cost, storage, and processing requirements. The relationship between resolution and cost is direct: higher resolution often results in higher costs, not only for acquiring the data but also for managing and processing it. Therefore, designing effective waste detection solutions requires careful consideration of the desired outcomes, timeliness, and cost-effectiveness to achieve the optimal balance.

2.3 Available Dataset

The availability of high-quality Earth Observation (EO) imagery has grown significantly in recent years, yet this increase has not been paralleled by the development of publicly available datasets annotated for training and evaluating waste detection methodologies. The absence of comprehensive and standardized datasets poses challenges for advancing research in this field. However, there are a few datasets specifically designed for solid waste detection from satellite images that provide valuable resources for the Wastereduce project.

One such dataset is *AerialWaste*, which focuses on the discovery of landfills from aerial images. The imagery for this dataset is collected from the Lombardy region in Italy, sourced from the Italian Agriculture Development Agency (AGEA), WorldView-3, and Google Earth. *AerialWaste* offers multiple levels of annotation, including binary labels indicating the presence or absence of waste, as well as multi-class, multi-label annotations that distinguish between 15 types of solid waste and 7 storage modes. Additionally, it provides metadata for weakly-supervised localization, including segmentation masks that outline relevant waste objects.

Another important dataset is *Automatic Detection of Landfill Using Deep Learning*, which contains geo-locations of large landfills from Asia, Europe, and South America. The images in this dataset are sourced from WorldView-3, WorldView-2, and GeoEye-1, and are annotated with a single class, including segmentation masks for more precise waste detection.

SWAD (Solid Waste Aerial Detection) is a dataset designed for detecting solid waste in aerial images. The images, collected in Henan Province, China, are sourced from Google Earth, WorldView-2, and SPOT. This dataset provides annotations for a single class and includes bounding boxes around the detected waste objects, aiding in the localization of waste within the imagery.

The *Global Dumpsite Test Data* dataset focuses on dumpsite detection across several large cities in Africa and Asia. Sourced primarily from Google Earth, this dataset includes annotations for four classes of waste—domestic, construction, agricultural, and covered—allowing for a more detailed categorization of waste types.

While these datasets represent significant progress toward creating a global repository for solid waste detection, they come with limitations. A major issue is that many studies do not release the datasets used for experimentation, or they lack detailed descriptions of the data, making it difficult to replicate, validate, or compare approaches. Furthermore, some datasets are region-specific with homogeneous backgrounds, which may limit the generalizability of models trained on these data to other areas with different land uses or terrain types. Others cover multiple regions but offer only binary annotations or a limited number of classes, which restricts the automatic classification of various waste materials. Additionally, for confidentiality reasons, most datasets do not publish the geographical coordinates of detected waste deposits, and they only provide a snapshot of the areas they cover, lacking temporal data necessary for evaluating the evolution of waste dumping over time.

3. Techniques applied in the Wastereduce project

The Wastereduce project leverages a comprehensive set of Earth Observation (EO) techniques and methodologies to detect, classify, and monitor solid waste sites across various landscapes, both terrestrial and aquatic, within the Natura 2000 network. Based on the available data and previous research, the techniques employed in this project are chosen to maximize accuracy, efficiency, and scalability. Different methodologies will be tested, each with a specific focus on handling the diverse data types and sources described in the earlier sections. These categories include visual interpretation, descriptive indices extraction, multi-factor analysis, features extraction and classification, traditional computer vision (CV) techniques, deep learning CV techniques, and other possible innovative approaches.

3.1 Visual Interpretation

Visual interpretation is a foundational technique in EO that relies on human experts to analyze and interpret satellite images. Despite the advancements in automated techniques, human interpretation remains valuable, especially in complex scenarios where automated methods may struggle to account for nuances. Within the Wastereduce project, visual interpretation will serve as a baseline method for verifying the outputs of automated systems and for interpreting complex cases that automated systems may flag as uncertain. This approach ensures that the results produced by the project are not only accurate but also contextually valid.

3.2 Descriptive Indices Extraction and Analysis

Descriptive indices derived from remotely sensed multispectral images are pivotal in identifying environmental conditions that may indicate the presence of landfills. In the Wastereduce project, several key indices will be extracted and analyzed to detect and monitor waste sites effectively. These indices include Land Surface Temperature (LST), various vegetation indices, domain-specific indices, and spectral signatures.

3.2.1 Land Surface Temperature (LST)

Land Surface Temperature (LST) is a crucial indicator for identifying large accumulations of solid waste. LST can be retrieved from the Thermal Infrared (TIR) channels of EO satellites and is used to estimate the surface temperature of the Earth. Large waste accumulations often exhibit higher surface temperatures due to the biological and chemical processes occurring within the waste, making LST an effective metric for landfill identification. In Wastereduce, LST data will be used to highlight potential waste sites by identifying anomalously warm areas that may correspond to waste decomposition activities.

3.2.2 Vegetation Indices

Vegetation indices, derived from multispectral channels, are another valuable tool for identifying landfills by detecting stress in vegetation that may result from waste accumulation. Several indices will be utilized in the Wastereduce project:

- *Normalized Difference Vegetation Index (NDVI)*: NDVI is the most widely used vegetation index, measuring plant health based on the reflection of sunlight at specific frequencies. Healthy vegetation reflects more near-infrared (NIR) light and less visible light, resulting in higher NDVI values. Conversely, stressed vegetation, which may be caused by underlying waste, exhibits lower NDVI values.

- *Normalized Difference Water Index (NDWI)*: NDWI is sensitive to changes in vegetation water content and complements NDVI by providing additional insights into vegetation health. This index can help detect areas where waste may be affecting water availability or quality.

- *Soil-Adjusted Vegetation Index (SAVI)*: SAVI is a modification of NDVI that accounts for soil brightness, making it particularly useful in areas with sparse vegetation. By adjusting for soil reflectance, SAVI provides more accurate vegetation health assessments in regions where landfills may be affecting both soil and plant life.

The detection of stressed or unhealthy vegetation using these indices can serve as a strong indicator of landfill presence, as waste sites often disrupt the natural environment and cause vegetation degradation.

3.2.3 Domain-Specific Indices

The Wastereduce project will also incorporate domain-specific indices tailored for the remote identification of particular waste types. These indices are designed to detect specific materials or contaminants associated with waste:

- *Oil Spill Index (OSI)*: OSI is used to map marine oil spills and can be applied in Wastereduce to detect oil-contaminated waste sites.

- *Floating Debris Index (FDI)*: FDI is specifically designed to detect floating plastic debris in marine environments. While its primary application is in oceans, it can also be adapted for identifying plastic waste in large bodies of water near landfills.

- *Olive Oil Mill Waste Index (OOMWI)*: OOMWI is used to identify potentially hazardous waste from olive oil production. This index will be employed in regions where such waste is prevalent and poses environmental risks.

- *Hydrocarbon Index (HI)*: HI is developed for detecting hydrocarbons on the ground surface, which are often present in industrial waste sites. This index will help in identifying areas contaminated with petroleum products or other hydrocarbon-based waste.

These domain-specific indices allow for the targeted detection of particular waste types, enhancing the overall waste detection capability of the Wastereduce project.

3.2.4 Spectral Signatures

Spectral signatures refer to the unique reflectance characteristics of different materials across various spectral bands. Large-scale landfills typically have distinct terrain compositions compared to other land uses, which can be identified through their spectral signatures. In the Wastereduce project, these signatures will be analyzed to pinpoint areas with high degradation potential, indicating the presence of waste. Although spectral signature analysis is not exhaustive and may not provide definitive identification of waste sites on its own, it is a valuable tool for highlighting areas with a high likelihood of hazardous waste accumulation. When combined with other indices and data sources, spectral signatures can significantly improve the accuracy of waste detection.

3.3 Multi-Factor Analysis

Multi-factor analysis is a sophisticated technique for predicting the presence and distribution of landfills by combining multiple geospatial and environmental variables. This method involves the creation of a spatial probability map that estimates the likelihood of landfill locations based on various factors associated with known waste disposal sites. In the Wastereduce project, multi-factor analysis will be employed to enhance the accuracy of waste accumulation detection and to better understand the environmental and socio-economic influences on waste disposal patterns. One of the key elements in multi-factor analysis is the integration of georeferenced information such as road networks, land cover maps, and other spatial datasets. These data layers are crucial for understanding how proximity to infrastructure and land use types influence the likelihood of illegal dumping or landfill establishment. For instance, areas near roads or industrial zones may have a higher probability of waste accumulation due to easier access for dumping activities. Studies have demonstrated that the combination of georeferenced data with other variables significantly improves the accuracy of landfill prediction models. For example, by incorporating road network data, researchers have been able to predict landfill locations more effectively, identifying regions at higher risk due to their accessibility (Biotto et al. 2009; Jordá-Borrell et al. 2014; Lucendo-Monedero et al. 2015). This approach will be utilized in Wastereduce to generate detailed risk maps, which can guide waste management policies and interventions. Population distribution is another critical factor in multi-factor analysis. By analyzing population density and its spatial distribution, it is possible to identify areas with a higher likelihood of waste generation and, consequently, potential landfill sites. Nighttime light imagery, often used as a proxy for population density, has been successfully applied in landfill detection studies to estimate waste generation hotspots (Karimi et al. 2022; Karimi & Ng 2022). In addition, economic and industrial indicators such as local economic activity levels, industrial output, and waste disposal frequency provide further insights into regions that might be prone to illegal dumping or the need for new landfill sites (Quesada-Ruiz et al. 2019; Abd-El Monsef & Smith 2019). Environmental variables such as vegetation indices, land surface temperature (LST), rainfall data, and distance from natural features (e.g., water bodies, forests) are also essential components of multi-factor analysis. For instance, vegetation indices like NDVI and SAVI can indicate stressed vegetation near landfill sites, while LST can reveal areas with elevated temperatures due to waste decomposition activities (Révolo-Acevedo et al. 2023). Rainfall data, on the other hand, can be used to assess the risk of

contamination from landfills due to runoff and leachate formation during heavy rainfall events.

Site Selection for New Landfills: multi-factor analysis is not only valuable for detecting existing landfill sites but also for selecting suitable locations for new landfills. By integrating GIS data with environmental and socio-economic variables, the Wastereduce project can identify areas where the establishment of new landfills would have minimal impact on the environment and nearby populations (Alexakis & Sarris 2014). This is particularly important for hazardous materials that require disposal in specially designed, environmentally safe landfills (Abd-El Monsef & Smith 2019).

Thus, multi-factor analysis in the Wastereduce project will combine georeferenced information, population and economic indicators, and environmental variables to create a robust predictive model for landfill detection and management. This approach will not only improve the accuracy of waste site identification but also could support sustainable waste management practices by guiding the selection of appropriate landfill locations.

3.4 Features Extraction and Classification

Features extraction and classification is a critical process in the detection of landfills using remote sensing data. By focusing on extracting key spatial and spectral features from satellite imagery, this technique helps reduce the dimensionality of the data and enhance the performance of detection models. This technique will be used in the Wastereduce project to improving the accuracy and reliability of waste site identification. Commonly, brightness features are among the most basic yet effective types of features that can be extracted from panchromatic images for landfill detection. These features, such as the mean value, dispersion, excess, and asymmetry coefficient, capture the variations in brightness across an image. In the study by (Vambol et al. 2019), these brightness features were computed from panchromatic images and subsequently thresholded to identify potential waste dumps. This method proved particularly useful in detecting areas with significant variations in surface reflectance, which are often indicative of waste accumulation. On the other side, combining spectral and spatial features is another approach that has shown promise in the detection of landfills. For instance, (Parrilli et al. 2021) combined spectral information from multispectral images with spectral features derived

from panchromatic images. This combination was based on brightness percentile intervals, which allowed for the extraction of both spectral and spatial characteristics relevant to waste detection. Additionally, spatial features computed from panchromatic imagery were particularly effective in identifying micro dumps and greenhouses, which might otherwise be overlooked in purely spectral analyses. The combined features were then processed using a Nearest Neighbor classifier, demonstrating the potential of this method to accurately classify and detect small-scale waste sites.

Spectral signatures, which represent the unique reflectance properties of different materials across various spectral bands, are another powerful tool for landfill detection. (Notarnicola et al. 2004) utilized spectral signatures to identify degraded areas associated with solid waste disposal sites. By employing an unsupervised classification technique, the authors were able to detect a recent landfill site even in the absence of thermal anomalies or vegetation stress indicators. The study highlighted the stability of spectral signatures over time, suggesting that multi-temporal comparisons could further enhance landfill detection by recognizing these stable features across different time periods. The ability to detect landfills through spectral signatures is particularly valuable when traditional indicators, such as thermal anomalies or vegetation indices, are not present or are difficult to detect. This method allows for the identification of waste sites in their early stages of development, potentially enabling more timely interventions to mitigate environmental impacts.

In the Wastereduce project, the combination of brightness features, spectral and spatial feature integration, and spectral signature analysis will be leveraged to increase the accuracy of landfill detection. By reducing the dimensionality of the data and focusing on the most salient features, these techniques will help improve the efficiency of detection models, allowing for the identification of waste sites across diverse environmental and geographic contexts. Features extraction and classification will play an important role in the Wastereduce project, enabling the development of robust, high-performance models capable of detecting and classifying waste sites with high precision. This approach will be essential for advancing the project's goals of improving waste detection and supporting sustainable waste management practices.

3.5 Traditional Computer Vision Techniques

Traditional computer vision (CV) techniques can play a crucial role in the Wastereduce project, particularly if applied in the detection and classification of

solid waste. These methods, well-established in the field of remote sensing, will be instrumental in our approach to analyzing multispectral images and identifying waste sites with precision. Specifically, object-based classification will be used. This method, which focuses on segmenting images into meaningful objects by merging pixels based on their spectral and spatial properties, has proven effective in previous studies for identifying complex features like landfills. By applying multi-resolution segmentation and the SLIC (Simple Linear Iterative Clustering) algorithm, we will try to improve our ability to detect waste sites by grouping pixels into superpixels, which will be analyzed collectively. This approach not only improves detection accuracy but also allows us to consider the context of pixel clusters rather than isolated pixels, which is essential for accurate waste identification in diverse environments. Pixel-based image classification methods will also be integrated into the Wastereduce approach, particularly for land cover classification. The project will benefit from models that apply both unsupervised and supervised approaches to classify pixels based on multispectral imagery. The success of unsupervised classification in previous studies, especially when higher spectral resolution images were used, suggests that this approach will be effective in localizing potential landfill sites across large areas within Natura 2000 pilot sites. This is particularly advantageous in scenarios where labeled data may be scarce, allowing us to efficiently analyze extensive areas with minimal prior information. Additionally, the Wastereduce project will utilize hybrid approaches, such as the combination of unsupervised clustering and supervised classification techniques. For example, employing a combination of K-Means clustering and a Light Gradient Boosting Model (LightGBM) to classify each pixel of a pansharpened image will enable us to detect offshore floating plastic waste and other challenging environmental hazards. The integration of these methods within the project framework will harness the strengths of both unsupervised and supervised techniques, resulting in enhanced detection capabilities across different environments, from terrestrial landfills to marine ecosystems.

3.6 Deep Learning Computer Vision Techniques

Deep Learning (DL) techniques have emerged as a powerful tool in the field of remote sensing, especially for the tasks of image classification, object detection, and semantic segmentation. In the Wastereduce project, leveraging these advanced DL methods will be critical for accurate and efficient waste detection from satellite and aerial imagery. A significant application of DL in waste

detection involves Convolutional Neural Networks (CNNs), which are well-suited for analyzing optical and multispectral images. In (Kruse et al. 2023) a semi-supervised approach utilizes both pixel-level and patch-level CNN classifiers. The pixel-level network, using a small CNN, extracts spectral features from individual pixels, which are then classified by a fully connected network. The patch-level network, on the other hand, focuses on spatial features within image patches, leveraging temporal data to address seasonal variations and enhance the differentiation between solid waste and objects with similar spectral properties. This dual approach helps in improving the accuracy of waste detection by incorporating both spectral and spatial information. Other approaches have utilized vegetation indices to complement spectral data in pixel-level DL models. For instance, (Lavender 2022) integrates vegetation indices with multispectral channels to classify each pixel. The network, comprised of fully connected layers, processes the spectral bands and outputs waste types or land use classes, which are further refined by a Decision Tree to enhance classification performance. The Wastereduce project will also consider semantic segmentation models based on DL architectures. In (Devesa & Brust 2021), a U-Net model adapted for multispectral images is used to generate binary masks indicating waste sites. To address the complexity of detecting specific waste types, such as construction and demolition waste in urban environments, (Yang et al. 2022) use the DeepLabv3+ architecture with an Xception backbone. This model performs semantic segmentation on high-resolution pansharpened images, effectively handling the intricate textures and spectral characteristics of such waste. In densely populated areas where traditional LST and vegetation indices might be less effective, (Torres & Fraternali 2021) develop a binary classification model trained on labeled optical images with varying ground resolutions. This model employs ResNet with a Feature Pyramid Network (FPN) to create a multi-scale feature representation, enabling it to detect a wide range of solid waste materials across diverse urban and extra-urban landscapes. In conclusion, the application of DL techniques in the Wastereduce project will leverage advanced CNN architectures and sophisticated models to enhance waste detection accuracy and efficiency. By integrating these methods, the project aims to address the challenges of identifying and classifying waste materials in various environments, ultimately contributing to more effective waste management solutions.

Conclusion

In order to effectively implement the Wastereduce project and achieve our goal of identifying, marking, and mapping locations of systematic waste accumulation in pilot sites of the Natura 2000 network, several types of data are required. The data needed based on the review we performed include:

1. High-Resolution Satellite Imagery:

- Multispectral and Hyperspectral Images: For detecting and analyzing waste types and accumulation patterns.

- Panchromatic Images: For detailed spatial resolution and accurate waste localization.

2. Thermal InfraRed (TIR) Data:

- Land Surface Temperature (LST): To identify thermal anomalies indicative of waste accumulation.

3. Vegetation Indices:

- NDVI (Normalized Difference Vegetation Index)

- NDWI (Normalized Difference Water Index)

- SAVI (Soil-Adjusted Vegetation Index): To assess vegetation health and stress which can indicate waste presence.

4. Domain-Specific Indices:

- OSI (Oil Spill Index)

- FDI (Floating Debris Index)

- OOMWI (Olive Oil Mill Waste Index)

- HI (Hydrocarbon Index): For targeted detection of specific waste types.

5. Geospatial Data:

- Georeferenced Information: Such as road networks, land cover maps, population distribution, economic and industrial indicators.

- Rainfall Data: To understand environmental conditions affecting waste dispersion.

- Nighttime Light Imagery: To estimate population density and potential waste generation areas.

6. Temporal Data:

- Multi-temporal Satellite Images: To analyze waste accumulation and changes over time.

The availability and reliability of these data sources will directly impact the choice and effectiveness of the analytical methods we apply. We will evaluate the methods based on the real-time availability of data, the accuracy of the techniques, and the time constraints of the project. Our approach will involve testing various methods to determine their suitability for our objectives. This includes exploring deep learning models, traditional computer vision techniques, and multi-factor analysis to identify the most effective strategy for waste detection and mapping. Given the constraints of data availability and project timelines, we will adapt our methods to ensure the best possible outcomes within the available resources. Finally, *it is important to note that University of Trieste hold the rights to review parts of the evaluation criteria to incorporate unanticipated data from Project Partners that may come up in the case documentation forms. Final adjustments to the evaluation criteria will be documented in the final deliverable of the activity D1.9.2.*

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