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Identifying and Ranking Landfill Sites for Municipal Solid Waste Management: An Integrated Remote Sensing and GIS Approach

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Abstract: Disposal of municipal solid waste (MSW) is one of the significant global issues that is more evident in developing nations. One of the key methods for disposing of the MSW is locating, assessing, and planning for landfill sites. Faisalabad is one of the largest industrial cities in Pakistan. It has many sustainability challenges and planning problems, including MSW management. This study uses Faisalabad as a case study area and humbly attempts to provide a framework for identifying and ranking landfill sites and addressing MSW concerns in Faisalabad. This method can be extended and applied to similar industrial cities. The landfill sites were identified using remote sensing (RS) and geographic information system (GIS). Multiple datasets, including normalized difference vegetation, water, and built-up areas indices (NDVI, NDWI, and NDBI) and physical factors including water bodies, roads, and the population that influence the landfill site selection were used to identify, rank, and select the most suitable site. The target area was distributed into 9 Thiessen polygons and ranked based on their favorability for the development and expansion of landfill sites. 70% of the area was favorable for developing and expanding landfill sites, whereas 30% was deemed unsuitable. Polygon 6, having more vegetation, a smaller population, and built-up areas was declared the best region for developing landfill sites and expansion as per rank mean indices and standard deviation (SD) of RS and vector data. The current study provides a reliable integrated mechanism based on GIS and RS that can be implemented in similar study areas and expanded to other developing countries. Accordingly, urban planning and city management can be improved, and MSW can be managed with dexterity.

Keywords: geographic information systems; landfill site selection; landfill site ranking; remote sensing; solid waste; solid waste management

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1. Introduction and Background

With the growth in global populations (particularly in cities), concerns regarding urban health are rising [1,2]. Various waste reduction techniques such as lean, total quality management, and six sigma have been presented to reduce and minimize waste [3,4]. The solid waste in the form of trash, garbage, and refuse daily dumped by urban and rural populations is known as municipal solid waste (MSW). Every year, around 1.3 billion tons of MSW are generated worldwide, which is expected to increase to 2.2 billion tons by 2025, with over a third of this MSW left uncollected [5]. The United States, Canada, Australia, Germany, South Africa, France, and the United Kingdom are among the highest per capita MSW-generating countries [5]. Expanding global urbanization, inadequate urban waste management, and a lack of resources around the globe contribute to the rise in MSW [6,7]. Every day, 0.74 kg of rubbish is generated per person in the municipality of Phnom Penh, Cambodia alone [8]. The World Bank claims that by 2050 the MSW generation will reach 3.4 billion tons [9]. Around 70% of MSW is dumped in landfills, while 19% of the waste is recycled, and 11% is used for energy generation. Among the world's current population, i.e., 7.6 billion people [10], around 3.5 billion have no access to basic garbage collection services [11].

Solid waste management aims at disposing of the garbage in the most environment-friendly manner possible. This is achieved through the assistance of the local people directly impacted by a region's solid waste program [12]. Solid waste is collected from houses, workplaces, small companies, and commercial enterprises. In the EU, this is considered a special waste stream. Such waste combined with the waste created during construction, renovation, and demolition is referred to as the MSW. Kitchen rubbish, paper and cardboard, yard waste, metal, plastic and rubber, electronic waste, glass, bricks, concrete, inert materials, and miscellaneous garbage are all examples of MSW. MSW is classified in various ways by global municipalities. It contains organic and inorganic components and biodegradable and non-biodegradable components. To minimize the generation of solid waste, various strategies are employed globally. Preventing, reusing, recovering, recycling, and disposing of waste are the most popular approaches to reducing solid waste [13]. The regular storage of solid waste is another strategy utilized to avert potential environmental hazards [14,15].

MSW management techniques differ by municipality, city, state, and nation based on the waste composition. Poor MSW management increases greenhouse gas emissions and has serious consequences for human health and environmental safety [16–18]. Different treatment and recycling processes are used globally for managing MSW. Classified recycling, incineration, landfilling, composting, and anaerobic digestion are some examples of MSW treatment and recycling procedures [19–21]. Most developing nations burn the MSW or gather and dump it at specific locations in the form of landfill sites [22]. For example, in Iran, the bulk of MSW is buried in open pits. Such open dumping poses long-term environmental and human health risks [6,23].

Landfill sites are commonly used for burying non-recyclable garbage across the world. These landfills must be inspected and compliance assured before being utilized as a solid waste dumping site. In addition, these landfills must meet regulatory, geographical, hydrological, and topographical requirements to manage and reduce environmental, economic, hygienic, and social concerns [1,24,25]. Nonetheless, rubbish is dumped into pits in several underdeveloped countries rather than buried in the ground. Despite the rapid development of alternate disposal techniques, the landfill in the forms of open dumping and sanitary landfill remains the most preferred disposal option in such countries. This is due to the lesser costs and technical requirements for such dumping in developing economies.

According to the United Nations Environment Programme (UNEP), open dumping and sanitary landfills account for 51% and 31% of waste disposal in Asia. Incineration and recycling account for just 5% and 8% of total waste. In Africa, open dumping and sanitary landfills account for 47% and 29% of total waste [26]. In North America, sanitary landfills account for 91% of garbage disposal [27]. It illustrates that most nations utilize landfills to dispose of their MSW, since it is less expensive than alternative options [28]. Landfills are used as approved locations for MSW dumping, with garbage processing and recyclable material sorting regulated before dumping. Landfilling is a frequently utilized procedure in municipalities worldwide for safe processing and disposing of solid waste [29,30]. Landfilling has long been a popular waste disposal practice in many developing countries [31]. This is because in such weaker economies, cost is the key factor and there is generally a lack of environmental considerations in developing countries. However, this must change in the era of striving for global sustainability and environmental protection. Accordingly, incentives must be provided to relevant stakeholders to conduct resource recovery operations and reduce the environmental burdens of such landfills.

On the other hand, incineration requires significant infrastructure investments and can create extremely high temperatures and adversely affect the climate and environment. Similarly, resource recovery processes such as pyrolysis, liquefaction, gasification, anaerobic digestion, and composting have extensive staffing, equipment, and cost requirements. Therefore, landfilling is preferred due to the cost-effectiveness and labor-intensive procedures in developing countries. Furthermore, the combined landfill may create profits by generating electricity from landfill gas and leachate. Landfilling is a common practice in developing countries; however, as previously discussed, this practice should not be encouraged, and more environment-friendly and sustainable approaches should be adopted. These include using greener materials, encouraging and incentivizing recycling, and other green initiatives aligned with the United Nations' sustainable development goals. Climate change cannot be tackled in the absence of such holistic measures and considerations for the environment. This also goes against the circular economy concept, which is at the forefront of global greening initiatives.

Overall, landfilling is still a prevalent MSW technique but cannot be termed as the best option unless actions are taken to transform the dump into something useful. For example, these landfills can be transformed from "garbage dumps" to "energy powerhouses" by installing integrated technology to generate recycled materials and renewable energy. According to Nabavi-Pelesaraei et al. [32], landfills and treatment facilities for domestic rubbish, hazardous chemicals, radioactive wastes, construction, demolition, and renovation wastes are all located in distinct areas that can serve as energy generation points. In addition, landfill mining reclaims valuable recyclables and combustible landfill gases from landfill sites to help free up landfill areas and promote sustainability [33,34].

Landfills can be divided into different classes based on the usage. Class 1 landfills are used for soil disposal. Class 2 landfills are used for mineral disposal and construction and demolition waste. Class 3 landfills are used for the disposal of MSW. Class 4 landfills are used for the disposal of commercial and industrial trash. Class 5 landfills are used for disposing of hazardous waste. Finally, Class 6 landfills are used for dangerous underground waste disposal [35]. In terms of types of landfills, the most common ones include secure landfills, monocle landfills, reusable landfills, and bioreactor landfills [36]. To stall harmful environmental consequences, the wastes are enclosed in secure landfills. The waste that cannot be treated by incineration or composting is dumped into monocle landfills. Reusable landfills enable rubbish to settle for longer periods before digging for recovery of metals, plastics, and fertilizers.

In terms of control, there are three types of landfills: semi-controlled, open, and sanitary landfills [37]. MSW dumped in an open environment is called an open dump landfill. Most developing countries have open dumps, where MSW is randomly discharged into low-lying open regions. In such poorly managed landfills, scavengers, other birds, mosquitoes, bugs, rodents, and deadly germs find a home, promoting health concerns.

Researchers have investigated various methods for choosing dumping or landfill locations globally. Scholars have used mathematical models to choose dump locations [38]. Based on the analytical hierarchy process (AHP), Lokhande et al. [38] used GIS to locate a trash disposal site. The same has been used by other studies [39–43]. For example, Spigolon et al. [40] determined landfill siting based on optimization, multiple decision analysis, and GIS. Şener et al. [41] selected solid waste disposal sites with GIS and AHP methodology using a case study in Senirkent–Uluborlu (Isparta) Basin, Turkey. Similarly, Sumathi et al. [42] used a GIS-based approach for optimized siting of municipal solid waste landfills.

A study was conducted in Iran using the GIS and multi-criteria decision-making methods (MCDM) [44]. GIS-based multi-criteria decision analysis (MCDA) and evaluation were used for landfill site selection in Ethiopia [45]. The authors used AHP and weighted linear combination models. In the city of Rudbar in Iran, with a harsh morphological and sensitive environment, fuzzy logic spatial modeling has been used for landfill site selection [46]. Wang et al. [47] selected waste disposal sites and highlighted the associated environmental risks. In Javanrud, Iran, trash was disposed of in a landfill using GIS and MCDA [23]. In Syria, GIS-based normalized difference vegetation index (NDVI) and normalized difference snow index (NDSI) techniques have been used to dispose of war trash [48]. GIS and RS have also been used for managing rising environmental problems of waste disposal [49]. In Pakistan, different combinations of satellite based bio-thermal indicators were used to monitor open dumps [50]. However, a study for identifying landfill sites for MSW has not been reported to date for Pakistan. This presents a gap targeted in the current study. For this purpose, integrated RS and GIS have been used in this study.

According to the literature, most researchers relied on judgments regarding numerous factors involved in their search for the best MSW disposal locations. These opinions were combined with GIS data to locate the landfill sites [1]. The GIS and RS data were used to create a rating system for identifying landfills that ranged from the least to the most acceptable. Similarly, rather than building new facilities, the authors suggested researching growing nations using a ranking system based on Thiessen polygons to locate appropriate locations meant for landfill development. The current study builds upon these works and aims to offer a forum for decision-makers to analyze feasible landfill expansion regions in Pakistan. This is evident in developed countries like Canada, where GIS and RS data are commonly utilized for making informed landfill decisions [51]. Accordingly, the site of a landfill expansion is selected using factors such as proximity to garbage sources to reap financial advantages from lower waste transportation costs and less severe environmental and health impacts [47].

The current study capitalizes on these relevant works. It is a novel attempt at locating appropriate landfill sites for dumping MSW in Pakistan. The classification is regardless of the type of landfills. The aim is to highlight and rank the sites that can later be categorized for various types of landfills in the following studies. The key objective of the current study is to analyze appropriate landfill locations for MSW disposal using integrated GIS-RS indices. For this purpose, Faisalabad, an industrial city in Pakistan, was used as a case study. Thiessen polygons were utilized for relevant area identification.

2. Study Area

Faisalabad, an industrial city with an area of 3344.9 sq. km, was selected as a case study for current research. It is the third-largest city in Pakistan by population, located in the rolling flat plains of northeast Punjab, as shown in Figure 1. It is an industrial center with many textile mills, large agricultural processing plants, electronic equipment, and the furniture industry. The city is 605 feet above sea level, with latitudes 30° and 31.5° north and longitude 73° and 74° east [52]. The average temperature of Faisalabad ranges between 39 °C and 27 °C. January is the coldest month, with an average of 17 °C and 6 °C, while June is recorded as the hottest month [53]. The average annual rainfall is only about 375 mm (14.8 in), and half of it occurs in the monsoon season. The population of the city is around 3.56 million as of 2018 [52], spreading over 118 union councils and approximately producing 1600 tons of MSW with a 0.45 kg/capita/day rate. This huge production of MSW must be dumped at a proper place (landfill sites). Currently, there is no appropriate system or landfill sites marked for the study area. As a result, most MSW is dumped at random sites near populated areas, creating both health hazards and environmental concerns. The current study addresses this problem by locating and ranking appropriate landfill sites for dumping MSW in Faisalabad.

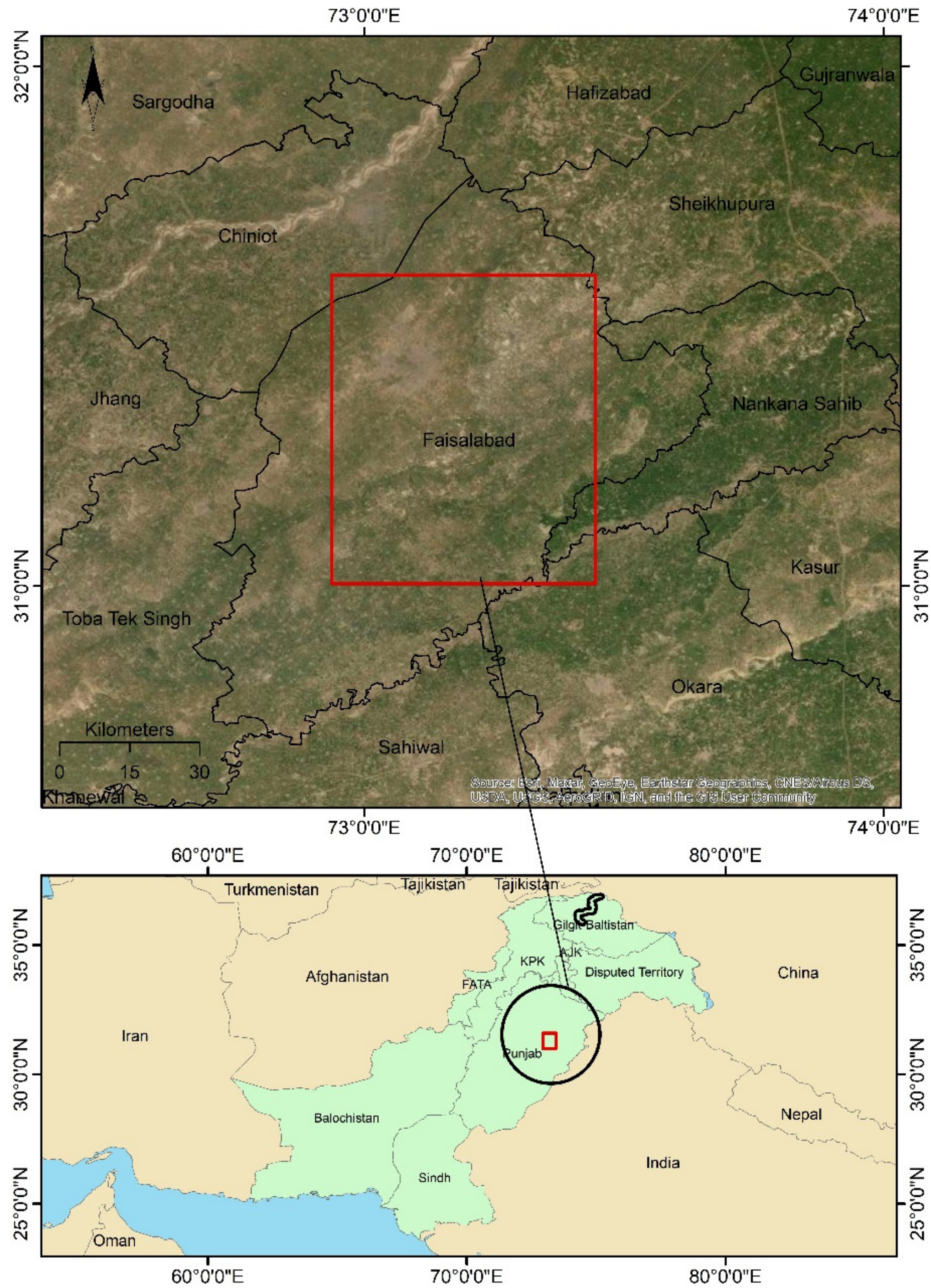

Figure 1. Study area—Faisalabad, Pakistan.

3. Methodology

The current research adopts a holistic methodology based on multiple steps. The methodology for identifying the landfill site in the current study is shown in the flowchart in Figure 2. The methodology is based upon vector data and RS rather than opinions from experts for the ranking of parameters. The resulting categories have been proposed based on landfill site suitability. Technology (GIS-RIS) suggested rankings have been used in this study instead of expert opinion, where the flat surfaces have been represented by Thiessen polygons. This flexible approach provides a competitive edge for pre-or post-decision making in areas where expert advice is not accessible.

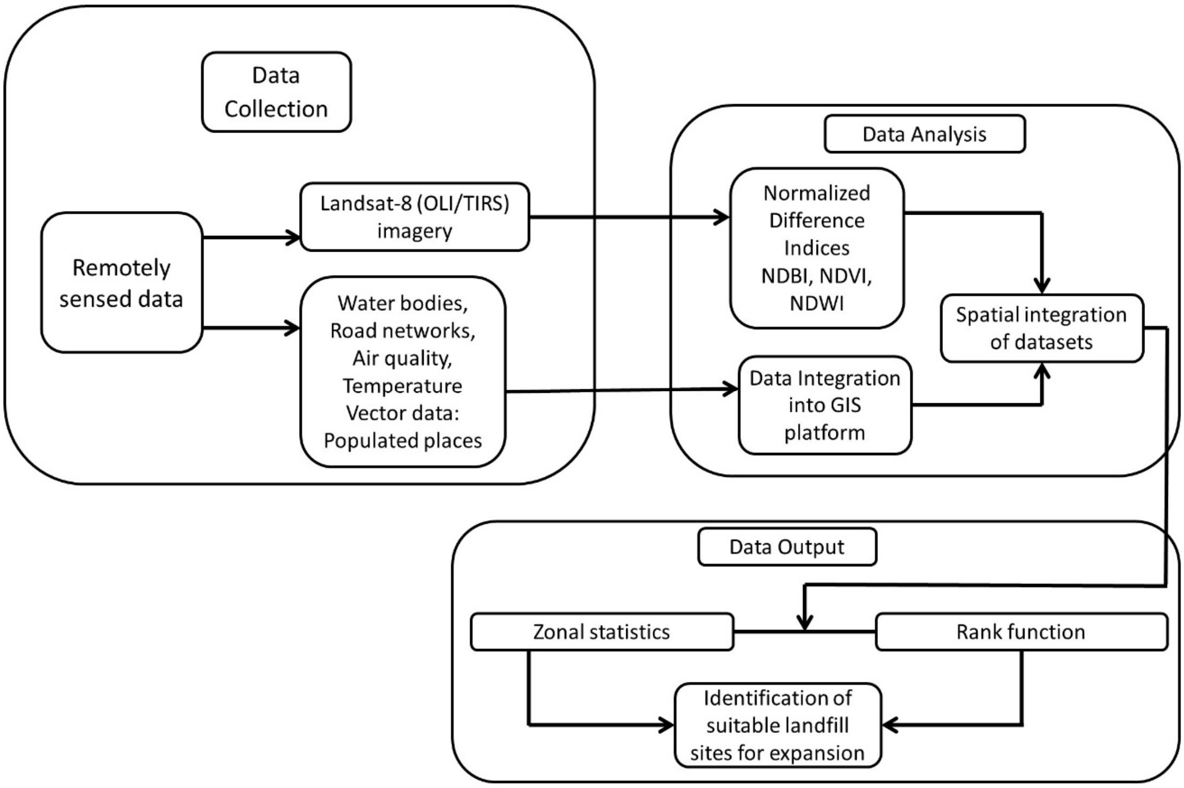

Figure 2. Workflow for landfill site assessment.

Furthermore, it is a self-contained approach that uses a mix of vector data and RS to identify and rank landfill area. The overall steps of the holistic methodology adopted in this study are presented in Figure 2. Accordingly, the three key steps include data collection, analysis, and output generation. In data collection, remotely sensed data from Landsat-8 (OLI + TRIS) was downloaded. It consisted of water bodies, roads, air quality, temperature, vegetation, population, and other details. In the data analysis stage, various normalized difference indices were used and spatially integrated using a GIS platform. Finally, the output stage involves a ranking function and zonal statistics to identify the suitable landfill expansion sites in the case study area. The associated datasets, indices, and polygon creation are subsequently discussed.

3.1. Satellite Dataset

Using path/row 144/052 with sensor Operational Land Imager and Thermal Infrared Sensor (OLI + TRIS) on 11/12/2021 and a spatial resolution of 30 m of Landsat-8 satellite, imagery for the study was obtained, as shown in Figure 1. The satellite imagery was acquired using Land viewer by EOS (https://eos.com/lv/ accessed on 20 March 2022). Imageries downloaded are of 30 m resolution, neglecting the cloud cover for maximum accuracy of <2%. Bands 2 (Blue), 3 (Green), 4 (Red), 5 (Near Infrared), and 6 (Infrared) of Landsat images were employed in the investigation (Shortwave Infrared). The three bands (2, 3, and 4), when combined, provide a natural color picture that may be used to determine the land use and land cover composition in the research region. Accordingly, this dataset has been utilized for the study area of Faisalabad in this research.

3.2. Creation of Theissen Polygons

Thiessen polygons are used for the analysis of proximity and neighborhoods. To produce Thiessen polygons, the distribution of sites in a specified distance is considered a parameter of influence. In this study, a Thiessen polygon mesh was created using nine suburban locations and villages for a 25 km radius of the district's headquarters. These locations include Lyall Pur Town, Chak Jhumra Town, Madina Town, Iqbal Town, Jinnah Town, Jaranwala Town, Tandliawala Town, Dijkot, and Summundari Town. Each polygon was numbered from 1 to 9 and given a unique ID. Thiessen polygons were originally produced using the ArcMap program, as shown in Figure 3.

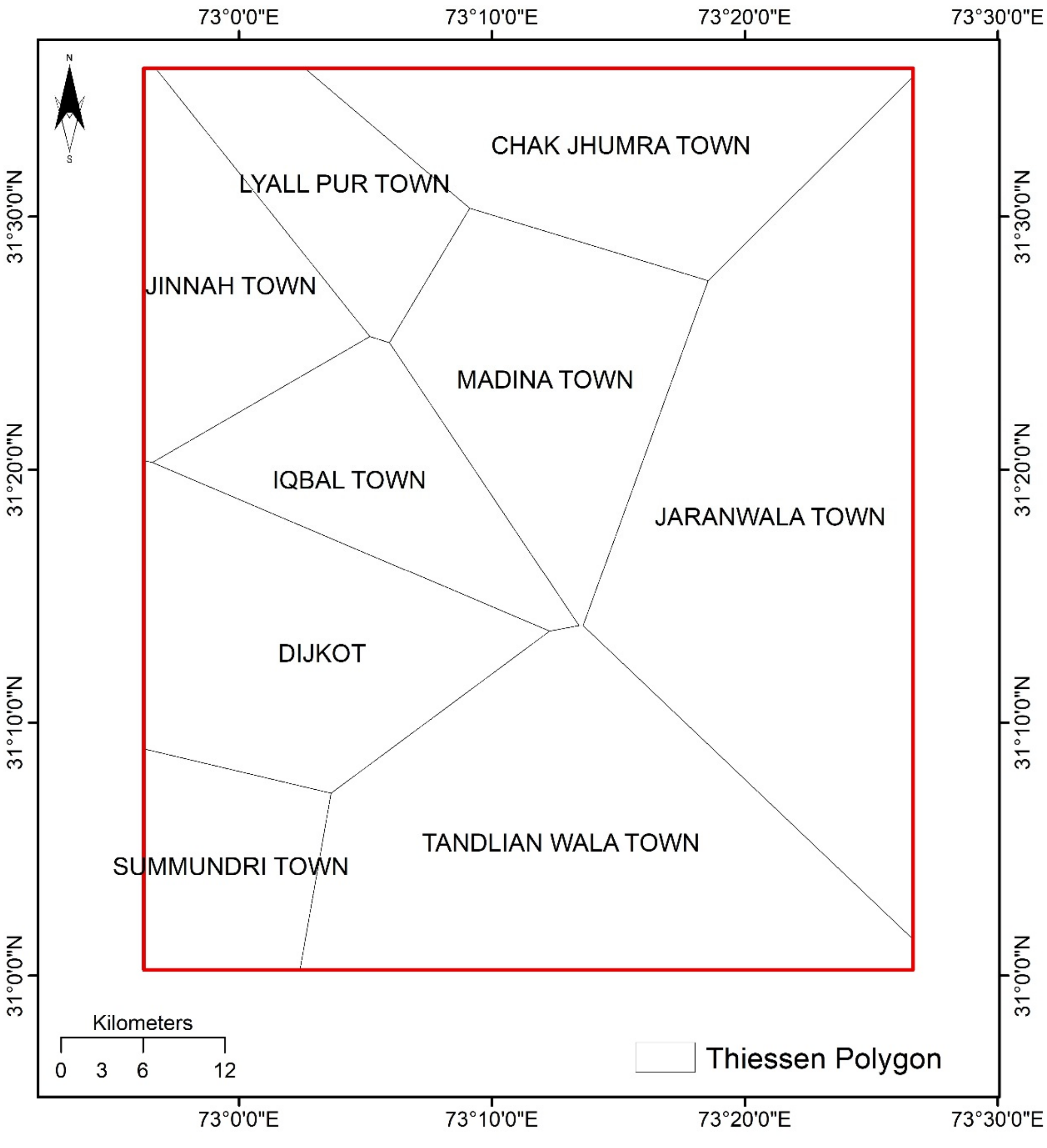

Figure 3. Thiessen polygons of the study area.

The Delaunay triangulation technique tool in ArcMap was used in this study to construct Thiessen polygons, following Richter et al. [54]. This approach verifies that the Delaunay criteria are discreet. The Delaunay criteria must be satisfied by the points formed in a triangular irregular network (TIN) [55]. Thiessen polygons are formed by bisecting each of the TIN's edges perpendicularly. This should ensure that the TIN's centers become the Thiessen Polygons' vertices [55]. In many studies [56–58], Thiessen polygons are more typically utilized in investigations involving hydrological factors and RS indices based on

Landsat-8 and include an NDVI. Multiple formulas are used for associated calculations, as given below in Equations (1)–(3):

For waste management [59],

$$(\text{Band } 5 - \text{Band } 4)/(\text{Band } 5 + \text{Band } 4); \tag{1}$$

For normalized difference moisture index (NDMI) [60],

$$(\text{Band } 3 - \text{Band } 5)/(\text{Band } 3 + \text{Band } 5); \tag{2}$$

For normalized difference built-up index (NDBI) [61],

$$(\text{Band } 6 - \text{Band } 5)/(\text{Band } 6 + \text{Band } 5). \tag{3}$$

3.3. Remote Sensing Indices

Multiple RS were used in this study, as shown in Figure 4. These include NDVI, NDBI, and Normalized Difference Water Index (NDWI). NDVI was used in this study because this metric indicates the density of greenness on the ground surface. Therefore, it is a critical consideration while looking for a good dump location [62]. The Landsat-8 OLI dataset was used to construct the NDVI using Equation (4).

$$\text{NDVI} = (\text{Bnir} - \text{Bred})/(\text{Bnir} + \text{Bred}) \tag{4}$$

where Bnir is a near-infrared band and Bred is the red band of Landsat-8. The NDVI value spans from −0.401 to 0.831. Barren terrain, open space, and rocky places have a lower value, grassland and shrub have a moderate value, and wide leaf rain forests have a higher value. Transient emissions have been reported to cause a decrease in the vegetation index surrounding landfills [63]. As a result, building landfills in places where the NDVI is lower will have a reduced impact on healthy vegetation [64].

The NDBI and associated calculations are used to assess the urban built-up size and geographical distribution of the study area. It also provides a comprehensive picture of urban land cover. The Landsat-8 OLI dataset was used to create an NDBI map in this investigation. Shortwave infrared (SWIR) and near-infrared (NIR) bands were employed for pertinent calculations, as given in Equation (5).

$$\text{NDBI} = (\text{Bswir} - \text{Bnir})/(\text{Bswir} + \text{Bnir}) \tag{5}$$

where Bswir is the shortwave infrared band and refers to Band 7 of Landsat-8. Bnir refers to Band 5 of Landsat-8. In this study, the computed value of NDBI varies from −0.269 to + 0.684. A higher NDBI value implies a significant concentration of built-up area and should not be considered for developing a sanitary landfill site [65]. Conversely, the lower number suggests a smaller concentration of urban built-up area, which may make landfill placement more acceptable [66].

The NDWI is used to measure the moisture content in plants and soil, which is calculated using Equation (6).

$$\text{NDWI} = \text{NIR} - \text{Swir}/\text{NIR} + \text{Swir} \tag{6}$$

where NIR has wavelengths ranging from 0.841 to 0.876 nm and SWIR wavelengths ranging from 1.628 to 1.652 nm. Water does not absorb this portion of the electromagnetic spectrum; hence, the index is resistant to atmospheric impacts. Furthermore, when monitoring forests, the NDWI index has a steadier fall in values when approaching critical anthropogenic load, making it a better predictor of the ecological status of forests than the NDVI.

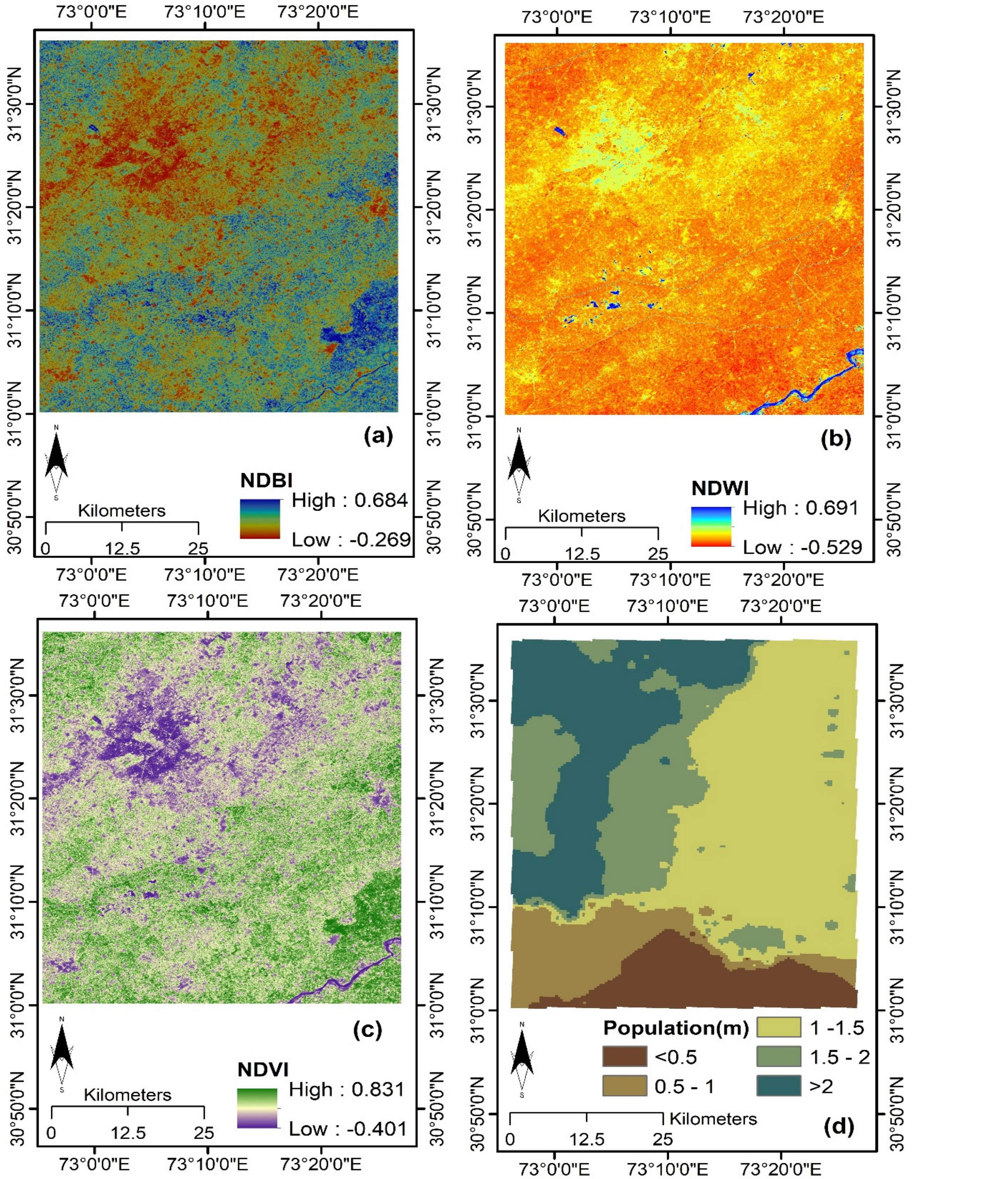

Figure 4. Normalized RS Indices and population distribution map of the study area. (**a**) NDBI, (**b**) NDWI, (**c**) NDVI, (**d**) Population.

High NDWI readings (in blue) indicate a high plant water content and a high plant fraction coating. Low vegetation content and cover with low vegetation correspond to low NDWI values (in red). The NDWI rate will drop during times of water stress. The presence of moisture in plant cover is determined using the NDWI index for determining fire danger, which can help tackle forest and bushfires. According to a recent study, landfills negatively influence the region's groundwater and surface water supplies [67]. As a result, the drier locations may be the better candidates for landfill growth to mitigate the possible negative impacts on local water supplies.

The population distribution map in this study was also obtained through Landsat-8, as shown in Figure 4. The thematic map shows the population of 9 chosen locations, as previously shown in Figure 3. Some have a population of fewer than 0.5 million, while others have more than 2 million. This irregular population distribution dictates the careful selection of landfill sites. Specifically, the areas with higher populations must be avoided for landfills.

4. Results

The GIS platform's "ranked overlay approach" provides an appropriate solution to examine the RS and vector data. A raster overlay approach was used for the gathered datasets to rank the attribute values and apply weightage to each map formed. The final overlay map was created by allocating weightage depending on the significance factor (see Table 1). The highest weightage was assigned to NDBI, followed by NDWI and NDVI. In addition, 26% of the area is declared a protected zone by the government and cannot be used for landfill purposes.

Table 1. Details of Weightage assigned to the Indices.

S No.	Parameter	The Weightage Assigned (%)
1	NDVI	18
2	NDWI	21
3	NDBI	35
4	Protected Area	26

From Figure 5, 70% of the study area was found to be appropriate for developing new landfill sites or the expansion of an existing dumpsite. A zonal statistics tool from GIS was used to rank the places with mean values based on the standard deviation (SD). This is a raster representation of the result in Figure 5. Accordingly, the study area is classified on a five-point scale for its suitability for landfills. The scale ranges from very good (dark green color) to very poor (dark red color). As expected, the area on the outskirts of the case study is more suitable for landfills. Specifically, the area in the southeastern suburbs is declared very good for landfill development and expansion. This area constitutes the regions of Jaranwala and Tandlian Wala towns.

4.1. Average Ranked RS Indices and Vector Data

RS indices and vector datasets of the study area are shown in Figures 6 and 7. With a mean value of 0.95, polygon 6, i.e., Tandlian Wala Town is selected as the best location for landfill site development and expansions. The order of ranks for polygon 6 in terms of physical factors shows a Waterbodies > Population > Roads pattern. The relative ranked mean indices for this polygon are NDBI > NDWI > NDVI. It indicates that the area of built-up regions and moisture is more than the vegetative area. However, it must be noted that the built-up areas in this region do not imply a higher population. On the contrary, this polygon has one of the lowest populations, as made evident by Figure 3. The collective sum of the mean indices and factors for polygon 6 is 1.321.

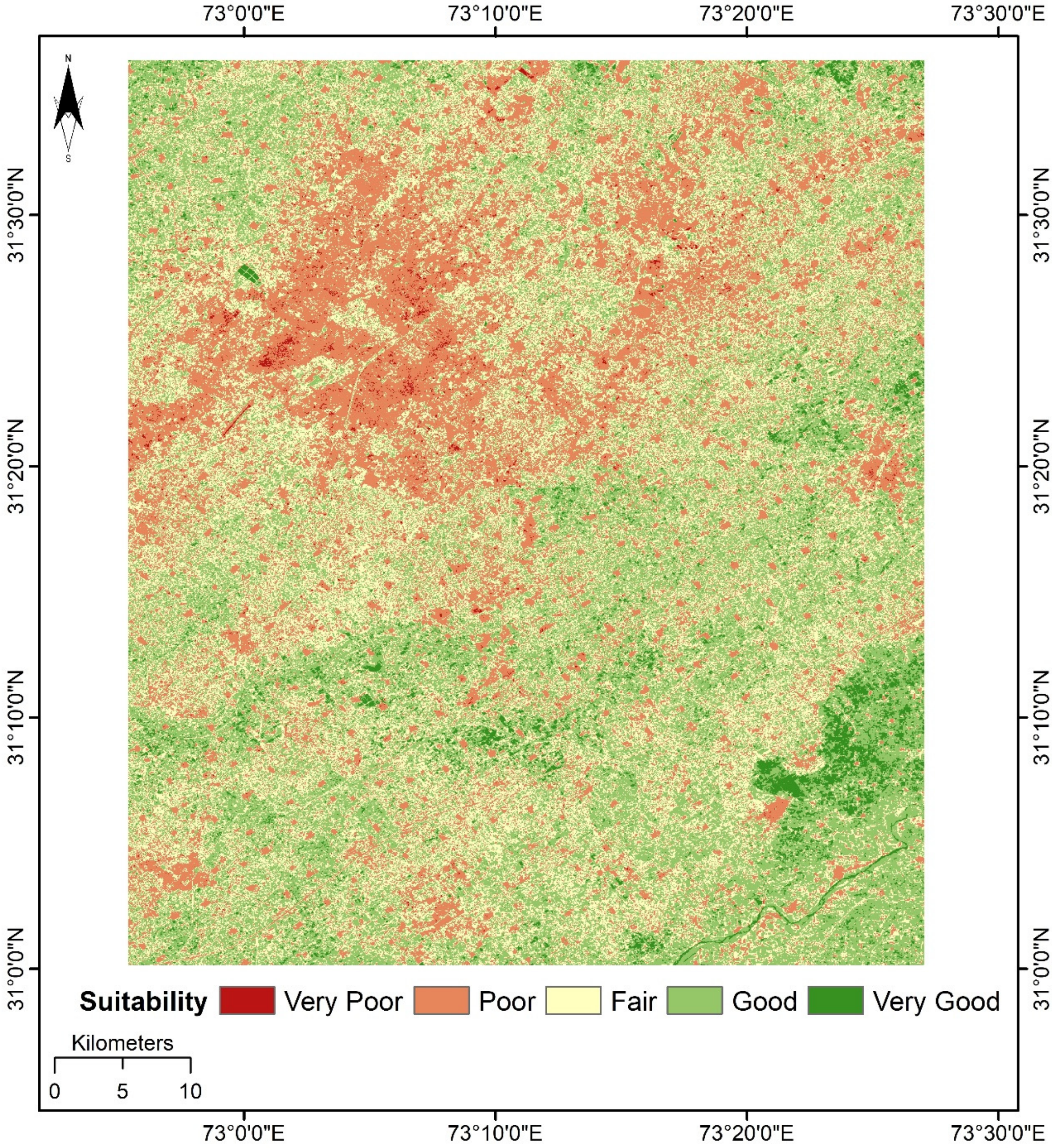

Figure 5. Suitability of Landfill sites.

Polygon 7 and 8 have been ranked as the worst for landfill site development, i.e., Madina Town and Lyallpur Town, with the order of ranks for the mean value as NDVI > NDBI > NDWI and NDBI > NDVI > NDWI, respectively. In these polygons, the results suggest that the water bodies are relatively small compared to the vegetation and built-up area. The distribution includes Water Bodies > Population > Roads when it comes to physical aspects. The sum of mean indices for polygons 7 and 8 are 0.37 and 0.44, respectively. It must be noted that these two polygons contain the most populated areas, as previously shown in Figure 3. Therefore, it makes more sense to avoid populated areas for landfill site development. Accordingly, the automated GIS tool shows similar ranks for these polygons, and hence these are the less preferred areas for landfill development or expansion.

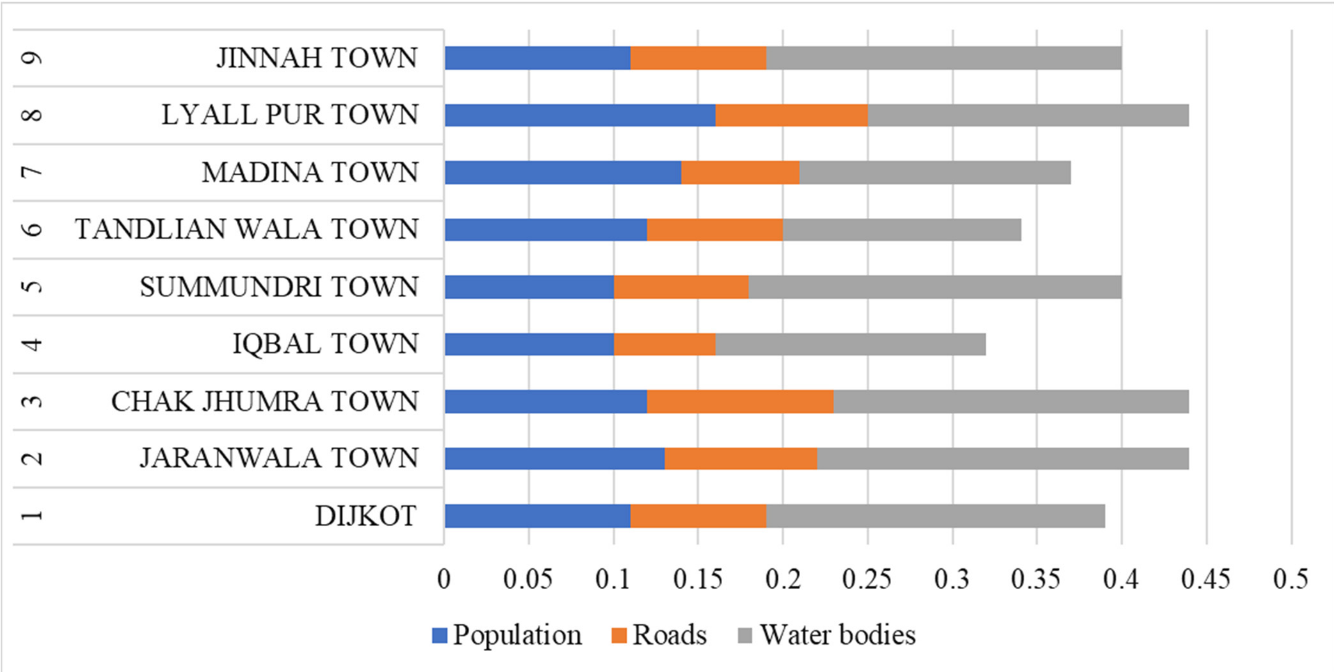

Figure 6. Relative ranked mean of the factors.

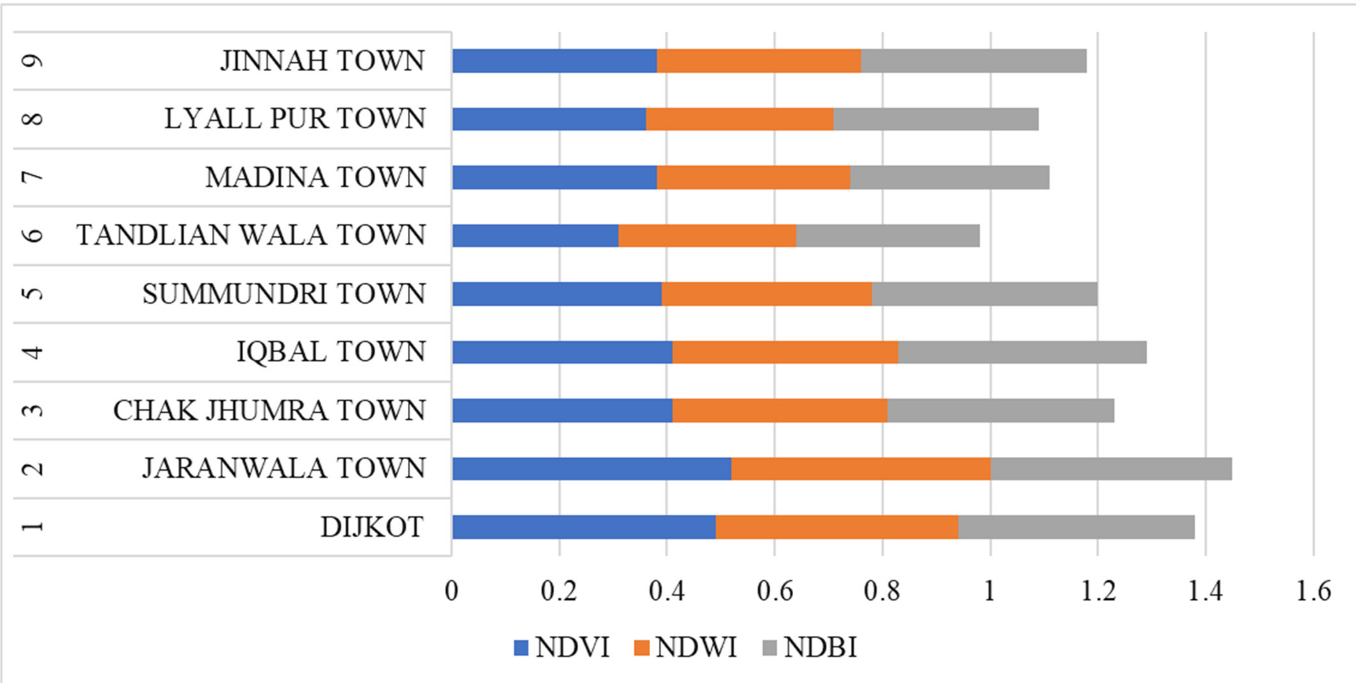

Figure 7. Relative ranked mean of the Indices.

Table 2 compares all polygons and shows the data for NDVI, NDBI, area, population, roads, and water bodies. In terms of area, Jaranwala Town, with an area of 795.9 sq. km, is the largest polygon, followed by Tandlian Wala Town, whereas Summundari Town has the lowest area. In terms of NDVI, the highest vegetation is recorded for Jaranwala Town (0.52), followed by Dijkot (0.49), whereas the lowest vegetation is observed in Tandlian Wala Town (0.31). For NDWI, the highest values are reported for Jaranwala Town (0.48), followed by Dijkot (0.45), whereas the lowest value is reported for Tandlianwala Town (0.33). In terms of NDBI, the highest built-up areas are reported in Iqbal Town (0.46), closely followed by Jaranwala Town (0.45), whereas the lowest value is reported for Tandlian Wala Town (0.34). In terms of water bodies, Jaranwala Town (0.22) has the highest value, closely followed by Chak Jhumra and Jinnah Towns (0.21), whereas Tandlian Wala Town (0.14) has the lowest value. As evident from the above discussions, the values for almost all assessment parameters are the lowest for Tandlian Wala Town, making it the best landfill development area for the city of Faisalabad.

Table 2. Relative ranked mean values of the indices and factors.

No.	Name	Area (sq. km)	NDVI	NDWI	NDBI	Population	Roads	Water Bodies
1	Dijkot	380.4	0.49	0.45	0.44	0.11	0.08	0.2
2	Jaranwala Town	795.9	0.52	0.48	0.45	0.13	0.09	0.22
3	Chak Jhumra Town	367.4	0.41	0.4	0.42	0.12	0.11	0.21
4	Iqbal Town	243.3	0.41	0.42	0.46	0.1	0.06	0.16
5	Summundri Town	166.1	0.39	0.39	0.42	0.1	0.08	0.22
6	Tandlian Wala Town	637.6	0.31	0.33	0.34	0.12	0.08	0.141
7	Madina Town	340.6	0.38	0.36	0.37	0.14	0.07	0.16
8	Lyall Pur Town	188.7	0.36	0.35	0.38	0.16	0.09	0.19
9	Jinnah Town	224.9	0.38	0.38	0.42	0.11	0.08	0.21

4.2. The Standard Deviation of RS Indices and Vector Data

After the basic comparisons of the RS indices for the 9 study polygons, the SD of the RS indices (See Figure 8) and the physical factors (see Figure 9) were calculated. The SD depicts the variance across polygons and is also used to support mean ranked sum maps. From Figure 8, Figure 9 and Figure it is evident that polygon 1, i.e., Dijkot, has the least sum of the SD of indices, with a value of 0.27. The associated grading is NDBI > NDWI > NDVI for RS indices and Population > Roads > Waterbodies for physical factors.

On comparing the indices values of all polygons, it was noted that polygons 7 and 8 have the highest NDBI and NDVI values. As a result, these polygons were deemed the least favorable for landfill extension based on the average SD and the physical parameters. According to the average ranking, 30% of the study area was deemed unsuitable for landfill growth. This is because the high SD value indicates less uniformity among the data. Also, it is noted that five out of nine polygons were suitable for landfill development, whereas the remaining four were deemed unsuitable. These least-favorable polygons have major water bodies and more population, making landfill development or expansion unfavorable.

Table 3 provides a comparison of the SDs of all polygons. In terms of NDVI, the highest SD is recorded for Lyall Pur Town (0.21), followed by Iqbal Town (0.16), whereas the lowest SD is observed for Dijkot (0.05). For NDWI, the highest SD values are again reported for Lyall Pur Town (0.16), followed by Jinnah Town (0.11), whereas the lowest value is reported for Dijkot (0.06). In terms of NDBI, the highest SD is reported for Madina Town (0.23), followed by Iqbal Town (0.18), whereas the lowest value is reported for Tandlian Wala Town (0.11). Finally, in terms of water bodies, Lyall Pur Town (0.13) has the highest SD value, closely followed by Iqbal Town (0.12), whereas Dijkot (0.05) has the lowest value.

Based on the above analyses, Figure 10 provides the holistic ranking of the study area polygons. The ranking follows a range from very good to very poor. Accordingly, Tandlian Wala Town is declared very good (the best in this case study) for landfill site development and expansion. Dijkot and Jaranwala towns are declared good (2nd best) for landfill site development and expansion. Chak Jhumra and Summundari towns are declared fair enough for landfill site development and expansion. Iqbal and Jinnah towns are declared poor sites for landfill development and expansion. Madina and Lyall Pur towns are declared very poor sites for landfill development and expansion. Based on the above, three polygons are declared good, two average, and four as bad for landfill development and expansion.

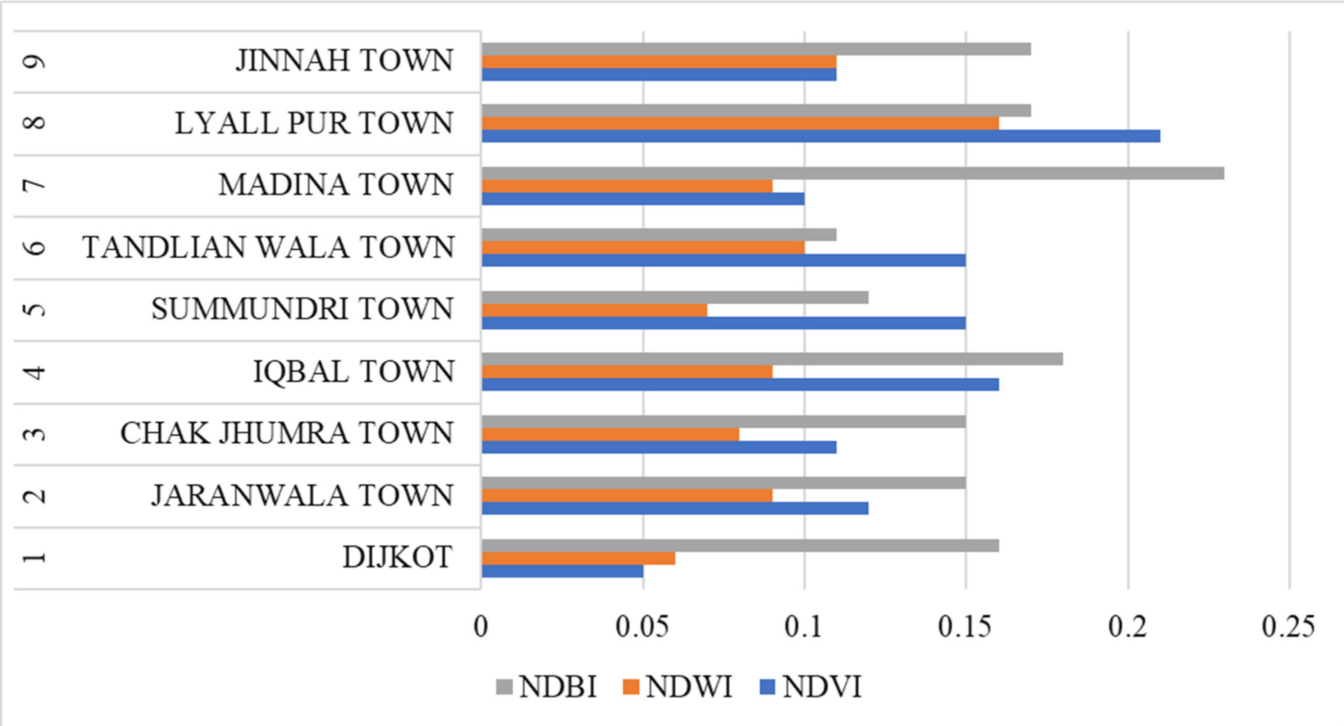

Figure 8. Standard deviation of the RS indices.

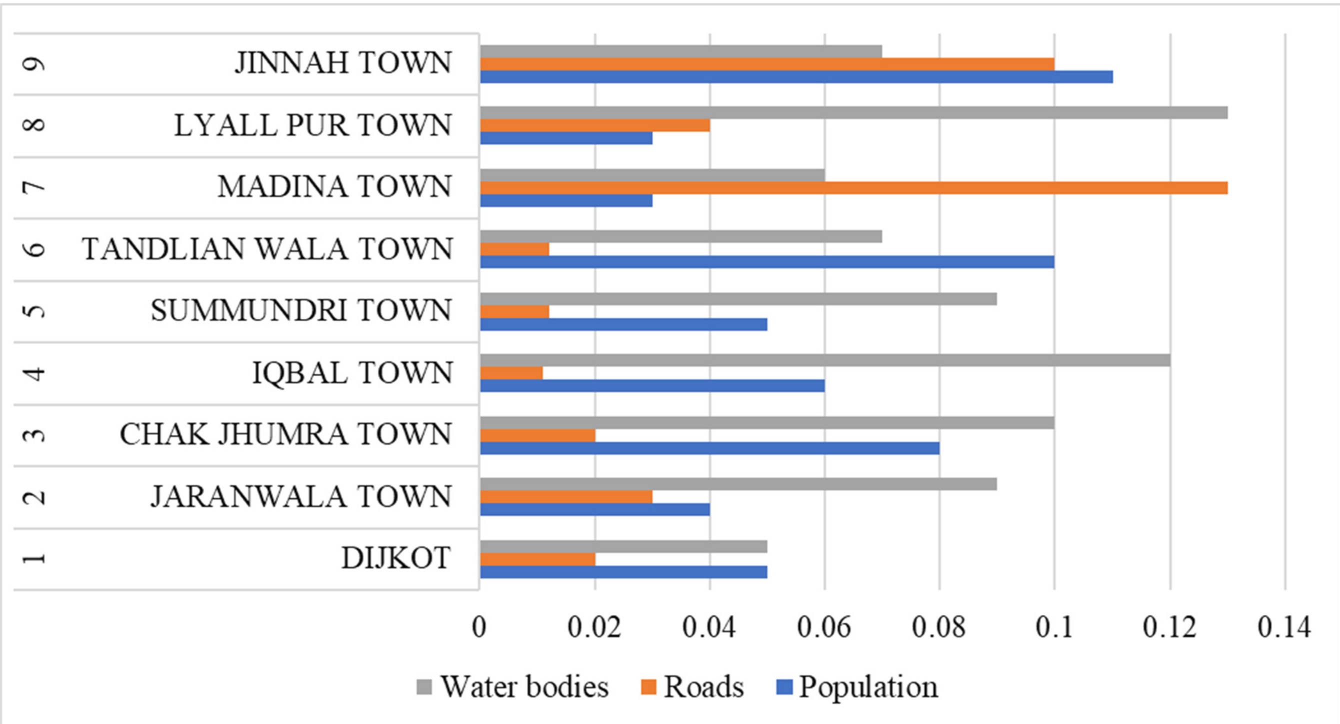

Figure 9. Standard deviation of the factors.

Table 3. Standard deviation values of the indices and factors.

No.	Name	Area (sq. km)	NDVI	NDWI	NDBI	Population	Roads	Water Bodies
1	Dijkot	380.4	0.05	0.06	0.16	0.05	0.02	0.05
2	Jaranwala Town	795.9	0.12	0.09	0.15	0.04	0.03	0.09
3	Chak Jhumra Town	367.4	0.11	0.08	0.15	0.08	0.02	0.1
4	Iqbal Town	243.3	0.16	0.09	0.18	0.06	0.011	0.12
5	Summundri Town	166.1	0.15	0.07	0.12	0.05	0.012	0.09
6	Tandlian Wala Town	637.6	0.15	0.1	0.11	0.1	0.012	0.07
7	Madina Town	340.6	0.1	0.09	0.23	0.03	0.13	0.06
8	Lyall Pur Town	188.7	0.21	0.16	0.17	0.03	0.04	0.13
9	Jinnah Town	224.9	0.11	0.11	0.17	0.11	0.1	0.07

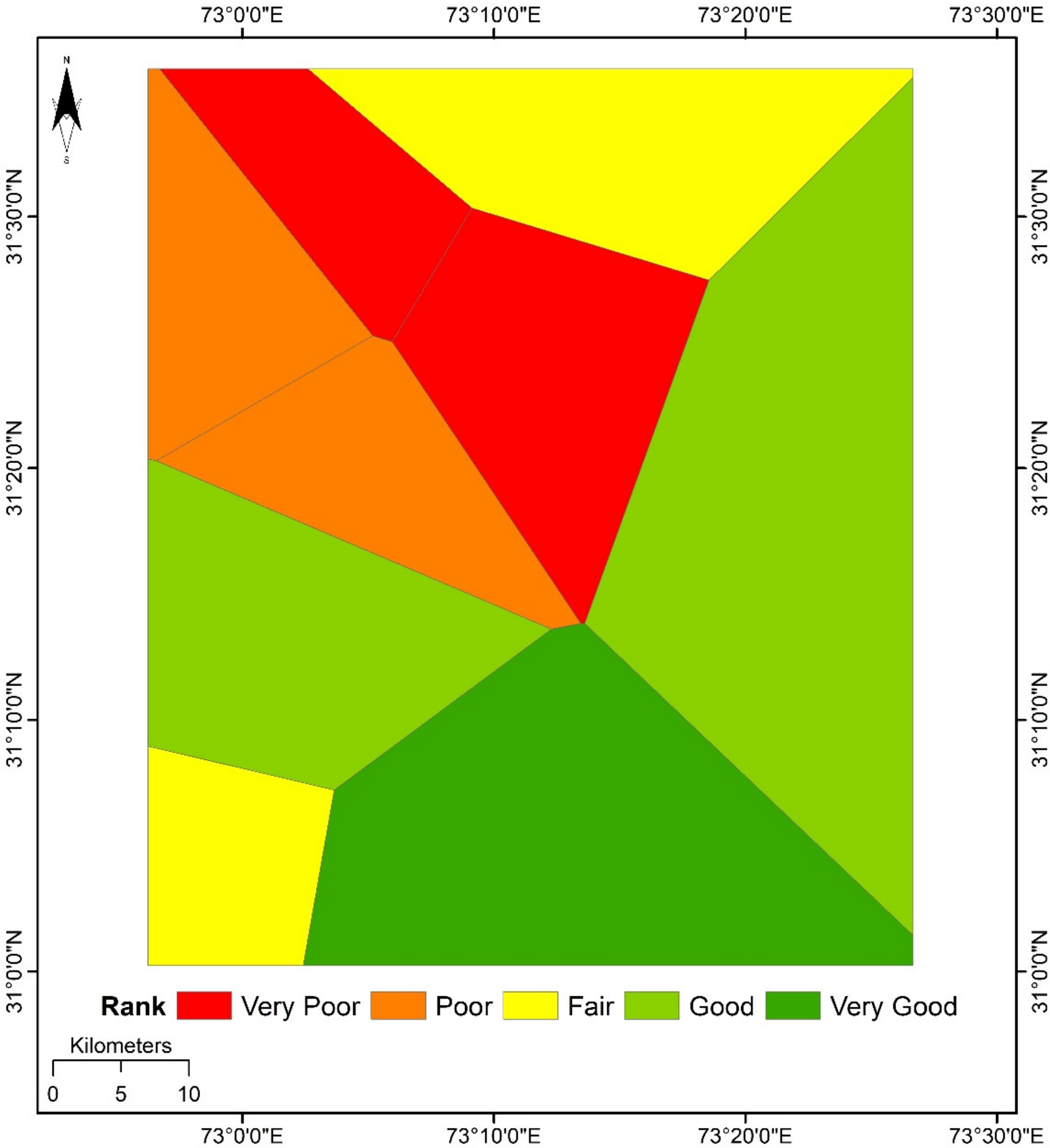

Figure 10. Ranked Thiessen polygons from Zonal Statistics.

As shown in Figure 11a, Tandlian Wala consists of a majority of agricultural land with less population and few water bodies. Thus, it is a very good site for landfill expansion for dealing with MSW. Further, if landfill mining is done for MSW in this zone, it would have fewer adverse effects on the environment and human population. Landfills in this polygon will have less hygienic, economical, environmental, and social expenses and meet the hydrological, geographical, topographical, and regulatory requirements in the case study area. Typically, landfill sites should be accessible by road to reduce the financial burden on the economies of developing countries like Pakistan [47]. Figure 11b shows that Madina and Lyallpur towns are densely populated residential areas, making them the least favorable for MSW landfills. The irrigation network is also shown in Figure 11, showing a denser presence in Tandlian Wala than in populated regions of polygons 7 and 8. There is more vegetated and agricultural area in Tandlian Wala than polygons 7 and 8. Therefore, landfill site development in polygons 7 and 8 will adversely affect the environment. Other relevant studies have not ranked the landfill areas, and only favorable and unfavorable areas were defined [48,65]. In comparison, this research ranks the entire area for the suitability of landfill sites based on RS and vector data.

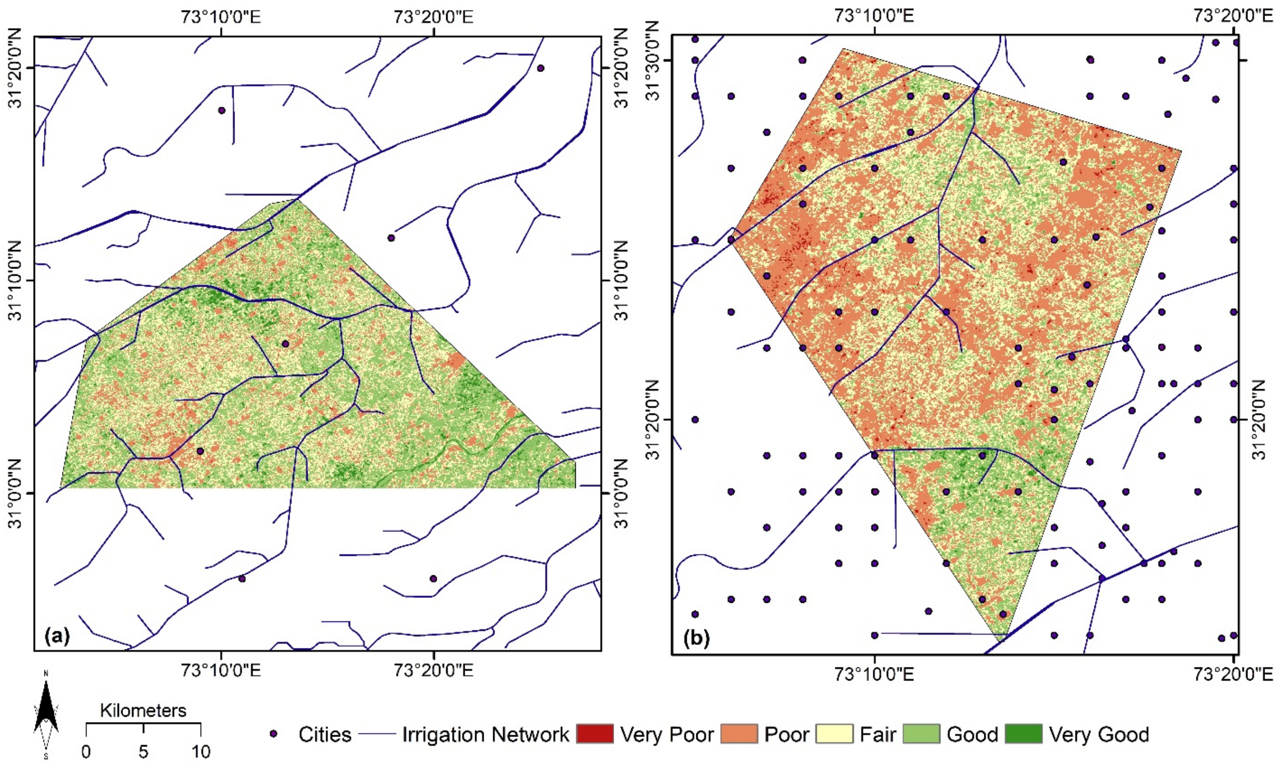

Figure 11. Irrigation network of the best and worst area. (**a**) water bodies in Tandlian Wala Town (**b**) irrigation network in Madina and Lyallpur towns.

5. Discussion

With the increasing population, solid waste production rises rapidly [1]. This issue is faced all over the world. USA, Australia, and Germany are among the largest producers of MSW [5]. Global urbanization, insufficient urban waste management, and a global shortage of resources all contribute to the growth of MSW [6].

Many studies have been conducted on selecting suitable sites for landfills. For example, mathematical models have been used to choose dump locations [38]. Likewise, AHP, RS, and GIS are used to locate a trash disposal site [40–43]. Also, the waste was disposed of in a landfill chosen using GIS and MCDA [23]. However, such a study for identifying MSW landfill sites in Pakistan has not been reported.

Integrated RS and GIS have been used in this study. Faisalabad city was selected for this study, and the area was divided into 9 polygons based on Thiessen polygons.

Then, these were ranked based on four datasets: NDVI, NDWI, NDBI, and population. Among these datasets, NDBI has the highest weight, i.e., 35%. Average ranked indices and SDs of all 9 polygons were calculated. Based on these SDs, polygons were ranked among the most suitable and least suitable for the MSW landfill site development and expansion. Polygon 6 is considered the best landfill site, and the physical factors ranking for this polygon following the pattern of Waterbodies > Population > Roads and indices as NDBI > NDWI > NDVI was displayed. Due to well-established transportation networks, fewer people, more vegetated areas, and the surrounding environmental factors, it is the most desired location for the landfill site. In contrast, the central and northwest portions (which include the towns of Iqbal, Jinnah, Madina, and Lyall Pur) are deemed unsuitable for landfill growth. This is due to the dense population and larger water bodies in the area, making them unsuitable dump sites.

The south of the study area is the most suitable region for landfill expansion, whereas the northwest parts are the least favorable. Overall, the polygons consisting of Tandlian Wala, Dijkot, and Jaranwala towns are declared suitable and preferred for landfill site development and expansion. Furthermore, the polygons comprising Chak Jhumra and Summundari towns are declared fair enough for landfill site development and expansion. Combined, these polygons constitute 70% of the total area. Finally, 30% of the study area was deemed unsuitable for MSW landfill site development and expansion.

Overall, the current study uses a combination of RS and vector data to locate and assess the best and worst landfill sites. In previous studies, only favorable and unfavorable landfill sites have been reported, but no ranking of landfill sites was conducted for developing countries [40,43,47]. For the sake of comparison, Madi and Srour [48] conducted multiple GIS analyses for landfill site management. However, the ranking using a holistic approach adopted in the current study has not been performed. Similarly, Ali and Ahmad [65] conducted GIS and AHP analyses to investigate the suitability of landfill sites in India but did not perform any rankings. In this context, the current study presents its additional novelty by conducting the first-ever landfill study for Faisalabad, Pakistan, and ranking the sites in a developing country.

The current study has both practical and research implications. Practically, town, city, and regional planners, city governance teams, environmentalists, and policymakers can use the method proposed in this study to mark landfill sites and reduce environmental concerns. This will help move towards smarter and sustainable cities. Similarly, in terms of research potential, the factors included in this study can be expanded to include more indices and physical factors to enhance the currently proposed method. Furthermore, a similar study conducted in developed countries and compared with developing countries will yield holistic results to add more value to the body of knowledge.

6. Conclusions

Due to rapidly expanding global urbanization, associated lack of resources, and inadequate urban waste management, MSW issues and management concerns are on the rise. Over a third of total municipal waste out of two billion tons generated remains uncollected worldwide. MSW is collected and disposed of at certain locations or burnt down in most developing nations. Landfill sites for solid waste must be inspected in terms of all requirements to reduce economic and environmental expenses. In this research, GIS and RS were used to rank the area based on Thiessen polygons for identifying landfill expansion from the most suitable to the worst sites. Landsat-8 data has been used for studying the landfill sites in the Faisalabad region of Pakistan. Nine Thiessen polygons were created and studied using GIS and RS techniques. For rankings, the indices of NDVI, NDWI, and NDBI were used. Further physical factors, including water bodies, roads, and population, were also used in reaching a holistic ranking for marking landfill sites in the case study area.

In terms of the assigned weights, four datasets consisting of NDVI, NDWI, NDBI, and population have been used in this study. NDBI has the highest weight (35%) among all indices. This study calculated the average ranked means and SDs of all indices and factors and represented them graphically and numerically. Polygon 6 (Tandlian Wala) is declared the best (very good) zone for landfill site development. The physical factor ranking for this polygon followed the pattern of Waterbodies > Population > Roads. For the indices, the pattern of NDBI > NDWI > NDVI was displayed.

Tandlian Wala (located southwest of the study area) is ranked the most suitable polygon for landfill site development, expansion, and mining. It is the most preferred place for landfill growth due to well-established transportation networks, smaller populations, more vegetated land, and the surrounding suitable environmental features. In comparison, the middle and northwest areas (consisting of Iqbal, Jinnah, Madina, and Lyall Pur towns) are ranked least suitable for landfill expansion. This is due to the dense population and higher water bodies in the area, making the conditions for landfill sites unfavorable.

In terms of limitations, the study is not all-inclusive and has room for improvement. First, the seasonal effect and long-term variation of all data sets are not considered in this study. These should be considered for getting better and more accurate results. Accordingly, future studies can map regions based on seasonal products and long-term variations of all data sets. Similarly, the method used in this study is limited to GIS and RS tools. In the future, it is suggested that advanced statistical machine-learning models be used with the current model to improve the overall accuracy.

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