Satellite based bio-thermal impact insights into MSW open dumps: a pair-unified proximity scenario

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**ABSTRACT**

Emissions from open Municipal Solid Waste (MSW) dumps are a serious threat to ecology in their close vicinity. Proper assessment of associated damage and its radial extent of influence constitute basic information to plan a sustainable remedial approach. This study emphasizes on twin dumping facilities as unified source of pollution in a geotechnical environment, and is limited to the use of freely available medium resolution satellite imagery to provide alternative of expensive ground measurements for obtaining base-level monitoring data to aid decision support systems in developing world. Proximity statistics have been applied to products derived from Landsat-8, with range and severity of hazardous influence being computed using curve flattening analysis of distance dependent profiles of various products. The combined average bio-influence and thermal-influence ranges of pair-unified dumps are 705 m and 1035 m, respectively. The developed methodology leads towards deeper understanding of seasonal changes in the influence zones, correlation amongst the two types of influence zones and relationship between severity and range of influence. The proximity statistical sequence has rendered the analysis sensitive enough to distinguish land covers having potential to cause misinterpretation of results by introducing effects in the bio-thermal continuum, similar to those of MSW emissions.

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1. **Introduction**

The unbridled population growth and associated economic activities have resulted in enormous rates of generation of Municipal Solid Waste (MSW) throughout the world (Khalil et al. 2018). MSW, a heterogeneous material also termed as ‘trash’ or ‘garbage, is an inevitable consequence of modern anthropogenic activities. It comprises daily use items like food, paper, bottles, electronics, furniture, clothing, product packaging, etc. Commercial, residential and agricultural wastes are the main sources of MSW (Abdel-Shafy and Mansour 2018). In poor countries, medical waste gathered from
hospitals and clinics, etc. is negligently mixed with MSW, exacerbating the perilous impacts on the environment and posing serious health threats. To minimize its hazardous impacts, MSW must be immediately collected, transported, treated and disposed of, once it is generated.

Although landﬁlling of MSW is at the bottom of the hierarchy of waste management solutions, it is the one most widely employed. Unsanitary landﬁll sites and open dumps of waste are very common in developing countries due to low budgets allocated for waste disposal, lack of skilled manpower and obsolete technologies to manage MSW in an efﬁcient manner (Karimi et al. 2019). An open dump is a region of space where solid waste is disposed of and exposed openly to the atmosphere and disease carriers, without taking into account the environmental risks associated with such practice. These dumps are situated in environmentally sensitive areas, such as in the vicinity of residential houses, wetlands, beaches, marshes, near water bodies, or public places (Babalola and Busu 2011; Gorsevski et al. 2012). Hence, the improper management of waste disposal facilities renders the poor nations most vulnerable to environmental hazards of openly dumped waste (Hazra and Goel 2009; Ali et al. 2014).

Solid waste disposed of in landﬁlls or open dumps goes through a combination of physical, chemical and microbial processes when it undergoes decomposition and degradation at the site (Chakma and Mathur 2017; Sarfraz and Farhan 2021). Consequently, it is transformed into various ﬂuid and gaseous complexes; commonly referred to as ‘Landﬁll Leachate’ and ‘Landﬁll Gases’, respectively. Leachate is the toxic wastewater rich in ammonium, nitrogen and organic matter, formed when water penetrates solid waste aiding the disintegration of waste (Tesseme and Chakma 2019; Sarfraz and Farhan 2021). Moreover, the biodegradation of organic matter results in the generation of landﬁll gases, which generally constitute 50–60% methane and 40–50% carbon dioxide, in addition to certain trace gases (Duan et al. 2021). Due to this biological and chemical degradation, solid waste is also a great source of heat to its surroundings and various studies have conﬁrmed micro-climatic, high-temperature environment present around open dumps of MSW (Faitli et al. 2015; Karimi et al. 2021). This excessive thermal energy is available in the form of sensible heat in the atmosphere and has the potential to aggravate Urban Heat Island effect in cities.

Amongst these harmful products of waste degradation, the ﬁrst two directly affect soil attributes in the vicinity of MSW dumps, which have an immediate inﬂuence on vegetation health. Any physio-chemical alteration in soil chemical properties from solid waste pollutants can seriously affect the growth and development of vegetation (Ruggero et al. 2019). This contamination of soil causes severe damage to plants, animals and human health and lessens soil productivity (Manzo et al. 2017). The effect of leachate on underground water depends on contaminants as well as the tendency of soils to retain water within. The changed soil chemistry due to metal contamination from leachate has an adverse impact on plants and biological organisms dependent on nutrients from the soil (Shayler et al. 2009). As a consequence, soil fertility and quality have signiﬁcantly changed due to heavy metal stress from agricultural, industrial and municipal waste sources over the last years.

Like other developing countries, the practice of unsanitary disposal of MSW is common in Pakistan which poses a great threat to soil productivity and groundwater
Due to this outdated system of waste disposal in open solid waste dumps, Pakistan has been facing a rapid decline in environmental conditions. Urban waste management is becoming a major source of nuisance to town planning authorities in cities; however, little has been done to improve the prevailing scenario. These problems can be solved with proper planning and management that requires scientific knowledge of the related issues and quantification of various environmental variables. Acquiring such knowledge to establish a platform for proper planning for sustainable solutions requires a heavy budget, trained manpower, latest monitoring instruments, etc. followed by a concrete proposal for their implementation to improve the living standard of communities. Unfortunately, in the developing world, the lack of such elements inhibits the establishment of a reasonable environmental monitoring and protection system, hindering sustainable development. So, there is a need to develop alternate methods and solutions for inexpensive environmental monitoring and assessment frameworks in such regions to provide firm support to decision-making entities for improved long-term planning (Faizi et al. 2020; Karimi et al. 2021).

The potential use and effectiveness of remotely sensed data for landfill monitoring have frequently been reported by researchers (Şener et al. 2006; Wang et al. 2009; Lacoboae and Petrescu 2013; Yan et al. 2014; Mahmood et al. 2015; Karimi et al. 2021). Remotely sensed data has a myriad of applications in the field of MSW management, ranging from its remote detection to environmental impact assessment (Manzo et al. 2017; Aderoju et al. 2018; Mahmood et al. 2019a). The identification or detection of MSW landfill sites in remotely sensed imagery requires high spatial and spectral resolution (Manzo et al. 2017; Faizi et al. 2020), whereas, the environmental impact assessment is effectively possible with moderate resolution satellite imagery (Yang et al. 2008). Studies emerging in the recent past have utilized satellite based Vegetation Indices (VIs) and Land Surface Temperature (LST) as bio-thermal indicators for monitoring the environmental hazards associated with MSW open dumps (Manzo et al. 2017; Karimi et al. 2021). The influence of varying geographical conditions on the bio-thermal influence of MSW dumps has been investigated by Mahmood et al. (2017), comparing two distinct MSW dumping sites and implementing the corresponding alteration in methodology. Mahmood et al. (2019a) made a detailed discussion over the intrinsic suitability of the three satellite based VIs based upon the correlation between volume of dumped waste and radius of the bio-influence zone, along with bias resulting from smoothing function. To supplement this notion of intrinsic suitability of indices, Mahmood et al. (2019b) included a new approach of max-min gap to assess the procedural stability of VIs to evaluate the level of confidence for both VI readings and individual seasons. Another addition to the previously established base was splitting of the winter season in two temporal windows and spatial adjustment of proximity zones.

This study makes use of multi-temporal Landsat-8 images for the monitoring and evaluation of bio-thermal hazards of Twin MSW Open Dumps in Faisalabad from 2016 to 2019. The establishment of a cost-effective and efficient framework of environmental monitoring and impact assessment in the developing world has been the primary aim behind this research work, with the objective of processing open-source satellite data to study the combined hazardous bio-thermal effects of closely spaced
MSW open dumps using an unprecedented twin-unified geospatial proximity analysis. Moreover, the current study also concentrates on seasonal parameters and associated bio-thermal behaviour of open dumps for this period, enabling the measurement of the extent to which openly dumped MSW will affect temperature and vegetation growth in its vicinity. In this regard, the bio-thermal indicators employed in this research are surrogate evidence for hazardous emission monitoring from MSW dumps. As an addition to the scientific knowledge established by previous studies, the use of a modified pair-unified geospatial analytical approach, quantification of the mathematical relationship between bio-influence and thermal-influence zones, and statistical identification of seasons most suitable for bio-thermal impact assessment of MSW open dumps are the central themes and novelty of this research work. For the very first time, the criterion used for optimum season selection for studying hazards of dumping sites has been established and proposed for future research in this regard.

2. Materials and methods

2.1. Study area

This study has been conducted for the third most populous city of Pakistan, Faisalabad, with an approximate population of 3.204 million. Geographically, it is located between latitudes 31.15°N to 31.63°N and longitudes 72.8°E to 73.3°E with an average altitude of 186 m above mean sea level. It covers an area of 5,856 km² (2,261 square miles) and has grown to become a major industrial center in the region. The geographical association of the study area is shown in Figure 1.
The climate of Faisalabad comprises very hot and humid summers with dry cool winters, features of a semi-arid climate (BWh) in the Koppen-Geiger classification. The average maximum and minimum temperatures for summer are 40.5 and 26.9 °C, respectively, whilst for winter the values are 19.4 and 4.1 °C, respectively. The hottest month is June when the conditions are dry and dust storms are common, whilst the coldest month is January with prevailing fog. The topography is marked by local depressions, valleys, and high grounds. The soil consists of very fine sandy loam which makes it weak in structure.

The city with its large number of industries and municipal units produces huge quantities of waste; 900 metric tons of MSW per day or above are disposed of openly without any precautionary treatment since no scientifically engineered sanitary landfill site is present. Presently, two sites have been authorized by town municipal authorities where the waste collected from the whole city is brought for disposal. These dumping facilities are located in close vicinity, one being older than the other. The disposed waste consists of both organic and inorganic matter with high moisture content. Both these sites are surrounded by agricultural land used for the cultivation of rice, sugarcane and wheat crops. Irrigation for these crops is mainly carried through canal water and due to improper drainage pattern; the area suffers from soil salinization. Moreover, the practice of waste dumping on these sites is creating complex socio-environmental problems, requiring attention from higher authorities to mitigate the risk of associated hazards.

Due to their proximity, common neighbourhood and significant overlapping of areas of hazardous influence, these twin dumping facilities satisfy all conditions of being a single polluting source for the environment. In fact, the hazardous influence zone of one dumping facility contains the second dumping facility inside it, making it unsuitable to distinguish the exclusive, individual bio-thermal influence of any of the dumping sites separately. Considering this situation, it appears logical not to treat these two dumps as individual pollution sources, distinct from each other. So in this study, these two sites have been unified for more meaningful and coherent analysis in terms of their hazard assessment and have been treated as a single point source of pollution. Geospatial bio-thermal analysis of twin-unified pollution sources in closed vicinity is the challenge addressed by the present study as an upgradation to existing unit pollution source assessment method.

2.2. Research methodology

This study intends to assess the collective bio-thermal effects of twin MSW dumping facilities of Faisalabad through quantification of the range and severity of surrounding hazardous bio-influence and thermal-influence zones. By definition, a bio-influence zone is a region around an MSW dump where the hazardous emissions, in any form, have a detrimental impact on bio-health, which in this particular case is the health of surrounding vegetation. Similarly, the thermal-influence zone around an MSW dump is the maximum radial extent to which heat emissions from the dump are sensible and effective, as determined by comparatively elevated temperature. To achieve the objectives, remotely sensed data captured from the Landsat 8 platform has been used
in this study. However, high-resolution imagery from QuickBird has been utilized for the demarcation of boundaries of the twin dumping sites.

2.2.1. Data acquisition and pre-processing

Data captured by Landsat 8 sensors OLI and TIRS spanning over 4 years, from January 2016 to December 2019 with spatial resolutions of 30 and 60 m, respectively, has been acquired having path and row index 149/38 encompassing Faisalabad dumping sites and neighbourhood. All scenes within this period were visually analyzed to check cloud cover on USGS earth explorer site from which 50 cloud-free images were requested for level-2 products. The brightness temperature (BT), Normalized Difference Vegetation Index (NDVI), Modified Soil Adjusted Vegetation Index (MSAVI) and Soil Adjusted Vegetation Index (SAVI) from Landsat Surface Reflectance high level data products were thus obtained. Following the hazard assessment method established by Mahmood et al. (2019a, 2019b), the aforementioned VIs were employed in the study to provide insight into the biological impact of open MSW dumps due to intrinsic and procedural stability, and MSAVI was chosen as the representative VI for further statistical analyses with thermal indicator due to its ability to adjust for soil signals, least EMA bias and accurate quantification of hazardous influence zone relative to the volume of dumped waste.

Brightness temperature derived from band 10 (10.6–11.19 μm) has been used to derive LST using single-channel algorithm, for which detailed mathematical framework can be found with Duan et al. (2019). Although previous studies make use of split window algorithm utilizing both bands10 and 11 to derive LST but due to large

![Figure 2. Landuse map.](image-url)
calibration uncertainty band 11 was not included in this study, as suggested by recent literature (Montanaro et al. 2014; Duan et al. 2019; Mahmood et al. 2021).

2.2.2. Landuse classification

Landuse map of the study area (Figure 2) was developed using Google Earth Engine platform, using Sentinel-2 imagery of the year 2020. Training datasets were visually interpreted with Sentinel-2 Optical imagery, Very High-Resolution images and ancillary data for six landuse classes i.e. built up, MSW open dumps, herbaceous crops, natural vegetation, water bodies and tree orchards. Random Forest (RF) classifier was selected to prepare Landuse classification map from Sentinel-2 imagery, as this particular combination has shown to achieve high classification accuracy for forested and agricultural landscapes as compared to other algorithms and datasets (Sothe et al. 2017; Noi and Kappas 2018; Waśniewski et al. 2020). The RF model was calibrated utilizing pre-processed optical images (Sentinel-2), topographic information and spectral indices (NDVI and NDBI) following which it was applied to the whole area of interest to generate a landuse map. For validation, a field survey was made to assess the accuracy of classification results. Kappa coefficient for the classification matrix was calculated to be 0.881, depicting the sufficiency of classification accuracy for this research work.

2.2.3. Ground survey

The ground truth data for assessment of landuse classification and general interpretation of bio-thermal curves was collected through surveys of study area, conducted in
Spring and Winter of 2020. The survey locations were chosen such as to encompass all landcover/landuse types present in the study area, and are illustrated in Figure 3.

2.2.4. Multi-level proximity zones

Multi-level proximity zones have been generated to analyze the spatial variations of bio-thermal characteristics away from MSW sites. Amongst these bio-thermal characteristics, phenomena of thermal energy emission and deteriorating plant health around the dumping sites have been selected for the study. With a radial extent of 30 m, a total of 50 buffer zones were constructed from dump boundaries (0 m) to a distance of 1500 m as shown in Figure 4.

The zonal statistics tool has been employed for the calculation of statistical parameters of LST and VIs in each concentric buffer zone. The evaluation of average zonal value leads towards the formation of distance dependent profile of an individual bio-thermal indicator in a graphical format. The particular distance at which the graphs get flattened marks the boundary up to which bio-thermal effects of openly dumped waste exist and there is no further change or definite trend in parameter value with increasing distance.

2.2.5. Smoothing of distance profiles

The graphs of distance dependent profiles generated from individual rasters contain anomalous variations and become complicated to analyze since the influence
boundary is not conspicuous enough to be marked and delineated. These anomalies or edgy patterns in distance dependent profiles arise due to possible local extraneous factors, other than the main central twin dumping facilities. To account for this problem, Exponential Moving Average (EMA) function has been utilized using bio-thermal profiles as a base. This function smooths out irregular variations in distance dependent curves to accurately estimate the boundary value of bio-thermal influence.

The analyses are based on seasonal windows to visualize the effect of meteorological conditions on bio-thermal zones around MSW open dumps. These seasonal windows (Table 1), except that of winter season, are defined by the local meteorological department. The winter season, having the longest span, was split into two smaller temporal windows for meaningful trend analysis. The individual intra-season values of bio-thermal zone boundary were averaged to obtain a single seasonal value for subsequent hazard assessment of bio-thermal influence.

### Table 1. Seasonal windows used for averaging.

| No. | Seasons     | Duration                        |
|-----|-------------|---------------------------------|
| 1   | Winter I    | 1 January to 10 March           |
| 2   | Spring      | 11 March to 30 April            |
| 3   | Dry summer  | 1 May to 6 July                 |
| 4   | Monsoon     | 7 July to 15 September          |
| 5   | Wet summer  | 16 September to 15 November     |
| 6   | Winter II   | 16 November to 31 December      |

3. Results and discussions

Two key ideas were central to conducting this research work. First, the temperature of MSW sites is expected to be higher than the surroundings due to biological and chemical degradation of solid waste releasing huge quantities of heat energy to the atmosphere. The temperature gradually decreases in moving away from the disposed waste until a certain point where its heating influence is not effective, marking the boundary of the thermal-influence zone of the central waste dumps. Second, vegetation vigour must be weakest near the waste dumping facilities owing to gaseous emissions and leachate movement towards adjacent areas. There should be a gradual improvement in vegetation health as the distance from the MSW dumps increases and at a certain critical distance, there will be no further improvement in VI values. This distance characterizes the boundary of the hazardous bio-influence zone of MSW open dump. These ideas were subsequently tested and the results achieved from proximity analysis of satellite based bio-thermal indicators around twin dumping facilities have been discussed in the following sections. The results depicted show consistency with the theoretical bases of the research framework. In addition, further analysis in this research work provides insights into the collective nature of bio-influence and thermal-influence zones as well as the effect of seasons on their behaviour.

The various values for hazardous bio-influence and thermal-influence zones for each season for all 4 years are given in Tables 2–4. Collectively, the twin dumps exhibit a mean influence range of 705 and 1035 m for vegetation health degradation and thermal emissions, respectively. The results obtained from distance dependent profiles of vegetation health and temperature corroborate both of the prior ideas.
Table 2. Temporal variations of bio-thermal-influence zones and their averaging around twin-unified source.

| Acquisition date | Radial extent zone (m) | Seasonal average (m) | Yearly average (m) |
|------------------|------------------------|----------------------|-------------------|
|                  | LST NDVI MSAVI SAVI   | LST NDVI MSAVI SAVI | LST NDVI MSAVI SAVI |
| **Year 2016**    |                        |                      |                   |
| 4 February 2016  | 810 360 360 360        | Winter I             | 855 360 390 360   | 1023 752 745 744 |
| 7 March 2016     | 900 360 420 360        |                      |                   |
| 24 April 2016    | 990 750 720 720        | Spring               | 990 750 720 720   |                   |
| 10 May 2016      | 1020 810 840 840       | Dry summer            | 1020 930 930 930  |
| 26 May 2016      | 1020 1050 1020 1020   |                      |                   |
| 15 September 2016| 930 780 750 750        | Monsoon              | 930 780 750 750   |
| 1 October 2016   | 1050 780 750 780       | Wet summer            | 1050 780 765 780  |
| 17 October 2016  | 1050 780 780 780       |                      |                   |
| 18 November 2016 | 1500 1050 1050 1050   | Winter II             | 1290 910 910 920  |
| 4 December 2016  | 1500 840 840 870       |                      |                   |
| 20 December 2016 | 870 840 840 840        |                      |                   |
| **Year 2017**    |                        |                      |                   |
| 6 February 2017  | 930 390 390 390        | Winter I             | 915 405 390 390   | 880 760 716 712  |
| 22 February 2017 | 900 420 390 390        |                      |                   |
| 26 March 2017    | 840 360 420 360        | Spring               | 910 680 700 680   |
| 11 April 2017    | 810 840 840 840        |                      |                   |
| 27 April 2017    | 1080 840 840 840       |                      |                   |
| 13 May 2017      | 990 870 840 870        | Dry summer            | 1030 990 990 980  |
| 29 May 2017      | 1020 1050 1050 1050   |                      |                   |
| 14 June 2017     | 1080 1050 1080 1050   |                      |                   |
| 17 August 2017   | 720 990 660 660        | Monsoon              | 720 990 660 660   |
| 18 September 2017| 720 660 600 630        | Wet summer            | 910 680 700 720   |
| 4 October 2017   | 1080 630 750 750       |                      |                   |
| 20 October 2017  | 930 750 750 780        |                      |                   |
| 21 November 2017 | 480 780 870 840        | Winter II             | 795 810 855 840  |
| 7 December 2017  | 1110 840 840 840       |                      |                   |
| **Year 2018**    |                        |                      |                   |
| 8 January 2018   | 1500 840 840 840       | Winter I             | 1178 473 488 503  | 1146 676 690 703 |
| 24 January 2018  | 1500 360 360 390       |                      |                   |
| 9 February 2018  | 930 360 390 390        |                      |                   |
| 25 February 2018 | 780 330 360 390        |                      |                   |
| 13 March 2018    | 480 330 360 360        | Spring               | 690 600 630 638   |
| 29 March 2018    | 450 390 390 420        |                      |                   |
| 14 April 2018    | 900 840 870 900        |                      |                   |
| 30 April 2018    | 930 840 900 870        |                      |                   |
| 16 May 2018      | 1020 840 810 1020     | Dry summer            | 1020 930 930 1020 |
| 1 June 2018      | 1020 1020 1050 1020   |                      |                   |
| 4 August 2018    | 960 300 330 300        | Monsoon              | 990 480 480 465   |
| 5 September 2018 | 1020 660 630 630       |                      |                   |
| 7 October 2018   | 1500 780 720 720       | Wet summer            | 1500 730 800 750  |
| 23 October 2018  | 1500 780 870 780       |                      |                   |
| 24 November 2018 | 1500 840 810 840      | Winter II             | 1500 840 810 840  |
| **Year 2019**    |                        |                      |                   |
| 27 January 2019  | 870 390 390 390        | Winter I             | 870 390 390 390   | 1092 639 648 656 |
| 16 March 2019    | 540 360 360 390        | Spring               | 495 375 390 405   |
| 1 April 2019     | 450 390 420 420        |                      |                   |
| 3 May 2019       | 1500 840 840 840       | Dry summer            | 1500 970 980 980  |
| 19 May 2019      | 1500 1020 1050 1050   |                      |                   |
| 4 June 2019      | 1500 1050 1050 1050   |                      |                   |
| **NA**           |                        |                      |                   |
| 24 September 2019| NA 660 660 660         | Monsoon              | NA                |
| 10 October 2019  | 1500 900 900 930       | Wet summer            | 1500 820 830 850  |
| 26 October 2019  | 1500 900 930 960       |                      |                   |
| **NA**           |                        |                      |                   |
about trends of bio-influence and thermal-influence of MSW dumping sites. Vegetation health profiles (depicted by VIs) show an inverse relation to distance from the dumping facility, whereas, thermal profiles depict the opposite trend. Hence, the idea that vegetation vigour improves in moving away from the MSW dumping site is validated along with the fact that the highest temperatures are recorded at the site of waste disposal in all seasons and tend to decrease gradually as we move away from the sites. These results of bio-thermal-influence trends show consistency with previous studies concentrating on MSW sites in similar climatic regions. A comparison with results obtained from a study on Mahmood Booti Municipal Solid Waste Open Dump (MB-MSWOD) situated in district Lahore, about 122 km away from the twin dumping facilities of Faisalabad, shows that both bio-influence and thermal-influence zones around MB-MSWOD had mean radial extents of 650 m (Mahmood et al. 2017). This resulted primarily due to the complex geographical setting and landcover distribution around MB-MSWOD as compared to the relatively uniform landcover type present around twin dumping facilities of Faisalabad. Similarly, a previous quantification of bio-thermal zones around the main MSW dump of Gujranwala district (Mahmood et al. 2019b), lying at a distance of 68 km from dumping sites of Faisalabad, revealed average bio-influence and thermal-influence zones of 590 and 480 m respectively, mainly due to difference in dump site area, amount of waste dumped and neighbourhood characteristics.

A consistent anomaly has been noted in the bio-continuum as a sudden drop in values at a distance of 1110–1290 m away from the twin dumping facilities. This trough is less pronounced in Winter I, whereas, it is more noticeable in other seasons. Moreover, it is sharper in the initial years 2016 and 2017, and loses perceptibility over time i.e. in 2018 and 2019.

Consistently, a crest at 1110–1290 m from the central dumping locations in the distance dependent thermal profiles can be seen, the very same distance at which a trough occurs in VI profiles. In a very similar manner as in VI profiles, this crest is least conspicuous in Winter I and is more noticeable in other seasons. Also, it is less pronounced in 2018 and 2019 as compared to 2016 and 2017 when it had a more pronounced profile.

The simultaneous observance of high-temperature and low VI values at a radial distance of 1110–1290 m from the central dumps suggests the presence of a non-vegetative landcover associated with heat-generating mechanism, especially in seasons other than winter. A ground survey made to understand this behaviour revealed the existence of two non-vegetative landcovers at these distances, a patch of barren land and a village, as highlighted in Figure 5. Both of the features have low to no

### Table 3. Seasonal Intensity (max-min gap) of bio-influence.

| Season/Year | MSAVI (10^-2) | SAVI (10^-2) | NDVI (10^-2) |
|-------------|--------------|--------------|--------------|
| Winter I    | 12           | 12           | 13           | 12           | 10           | 10           | 11.5         | 10           | 14           | 10           | 13.8         |
| Spring      | 4            | 3            | 5            | 4            | 5            | 4            | 4.5          | 4            | 5            | 5            | 4.5          |
| Dry summer  | 2            | 3            | 2            | 6            | 3            | 4            | 4.5          | 4            | 5            | 4            | 4.5          |
| Monsoon     | 4            | 8            | 5            | 5.7          | 5            | 8            | 6            | 6.3          | 6            | 10           | 6            | 7.3          |
| Wet summer  | 4            | 2            | 5            | 5            | 4            | 3            | 4.5          | 5            | 3            | 5            | 4.5          |
| Winter II   | 5            | 5            | 6            | 5.3          | 6            | 4            | 8            | 6            | 9            | 8            | 10           | 9            |

| Season/Year | MSAVI (10^-2) | SAVI (10^-2) | NDVI (10^-2) |
|-------------|--------------|--------------|--------------|
| Winter I    | 12           | 12           | 13           | 12           | 10           | 10           | 11.5         | 10           | 14           | 10           | 13.8         |
| Spring      | 4            | 3            | 5            | 4            | 5            | 4            | 4.5          | 4            | 5            | 5            | 4.5          |
| Dry summer  | 2            | 3            | 2            | 6            | 3            | 4            | 4.5          | 4            | 5            | 4            | 4.5          |
| Monsoon     | 4            | 8            | 5            | 5.7          | 5            | 8            | 6            | 6.3          | 6            | 10           | 6            | 7.3          |
| Wet summer  | 4            | 2            | 5            | 5            | 4            | 3            | 4.5          | 5            | 3            | 5            | 4.5          |
| Winter II   | 5            | 5            | 6            | 5.3          | 6            | 4            | 8            | 6            | 9            | 8            | 10           | 9            |

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vegetation cover resulting in lower values of vegetation health indices and higher temperatures. Other non-vegetative patches in the study area exist as well but being smaller and scattered in the form of fragments in the entire region, their collective effect is minimized in all the proximity zones and hence, does not create a significant anomaly.

3.1. Seasonal relationship of bio-thermal-influence zones

An interesting observation of this study based on 4 years of data was that for all seasons, the extents of thermal-influence and bio-influence zones were proportional to each other and obeyed a direct relationship i.e. large extents of bio-influence zone were simultaneously observed with large extents of thermal-influence zone and vice versa. This pattern can be visualized in Figure 6, in which the average four-year values of hazardous influence zone calculated from VI and LST curves corresponding to each seasonal window have been graphed.

It can be construed from Figure 6 that the lowest extents of bio-thermal-influence zones are observed in Winter I, whilst highest extents are encountered in Dry summer. The inter-season behaviour of bio-thermal influence is nearly identical, except from Wet Summer to Winter II. The transition of atmospheric temperatures from high in Wet Summer to very low during a period from November to December (Winter II) slow down the biological and chemical degradation process of solid waste, reducing the heating effect around open dumps and restricting the size of thermal-influence zone. This effect of temperature on the rate of biological and chemical degradation of waste has frequently been reported in MSW literature (Wang et al. 2012; Zhao et al. 2016; Chakma and Mathur 2017). In this very same period, the wheat crop is sown and is in its initial stage with minimal plant cover around the dumping sites resulting in low VI values. As a consequence, the distance threshold for stabilizing and levelling of VI profiles in distance-based graphs is generally higher, resulting in a large extent of bio-influence zone around the waste sites. It is the reason behind the contrasting behaviour of bio-influence and thermal-influence zone patterns from Wet Summer to Winter II. In Winter I, when the wheat crop has matured with a lush green canopy cover around the dumping sites along with the continuity of low atmospheric temperatures, both the bio-influence and thermal-influence have fallen to their least spatial extents.

Table 4. Seasonal extent and Intensity (max-min gap) of thermal influence.

| Season/Year | 2016 Radial extent (m) | 2017 | 2018 | 2019 | Average | 2016 Max-min (10^-1 K) | 2017 | 2018 | 2019 | Average |
|-------------|-------------------------|------|------|------|---------|------------------------|------|------|------|---------|
| Winter I    | 435                     | 915  | 593  | 810  | 688     | 22                     | 35   | 20   | 20   | 24.3    |
| Spring      | 1020                    | 910  | 675  | 465  | 768     | 35                     | 35   | 35   | 35   | 35      |
| Dry summer  | 1005                    | 1020 | 1035 | 1040 | 1025    | 22                     | 20   | 25   | 25   | 24.3    |
| Monsoon     | 900                     | 690  | 930  | –    | 840     | 18                     | 20   | 20   | –    | 19.3    |
| Wet summer  | 1080                    | 950  | 990  | 1030 | 1013    | 20                     | 25   | 25   | 30   | 25      |
| Winter II   | 1060                    | 780  | 900  | –    | 913     | 25                     | 20   | 20   | –    | 21.7    

Supposing that the biological and chemical degradation of waste in a central MSW dump, generating thermal radiations, determines both the temperature and health of vegetation in its surroundings and is the major cause of similar patterns of the radial
extent of bio-thermal hazardous influence zones, a predictive relationship between thermal-influence and bio-influence zone was hypothesized. For testing this hypothesis, regression analysis with the thermal zone as the predictor variable and bio-influence zone (derived from MSAVI profiles) as the criterion variable (dependent) was performed as depicted in Figure 7. MSAVI was chosen as the representative VI for input data of hazardous zone extent in regression analysis since it gives the most accurate relation of central waste dumped and the hazardous zone size, along with the best visualization of vegetation health trend away from the open dumps (Mahmood et al. 2019b). In this regression analysis, for every particular seasonal window, the average 4-year value of the thermal-influence zone was plotted against the average 4-year value of bio-influence zone. It was observed that the data closely fits a regression line $y = 0.6303x + 428.58$ with an $R$ squared coefficient of 0.8367, implying...
a high strength of relationship between the model equation and the dependent variable i.e. bio-influence zone. Also, the correlation coefficient between these two sets of variables was calculated to be 0.9147, signifying a high degree of direct relationship.

To have a further understanding of the seasonal behaviours of bio-influence and thermal-influence zones and their mutual relationship, correlation coefficients were calculated to evaluate the degree of relationship between radii of thermal-influence and bio-influence zones in each seasonal window for the four-year period. In this analysis too, MSAVI was chosen as the representative VI for providing the bio-influence zone extent. As a result, correlation coefficients for Winter I, spring, dry summer, wet summer, monsoon, and Winter II were found to be 0.620, 0.829, 0.149, 0.576, 0.2617 and 0.219, respectively.

From these values of correlation coefficients, it can be inferred that the extents of thermal-influence and bio-influence zones show the strongest positive relationship in Spring and Winter I. The reason for such behaviour is that in these seasons the radius of hazardous zones is exclusively determined to a large extent by the
decomposition of waste, generating thermal radiations that affect the surrounding temperature and vegetation health. Whilst in the rest of the year, the high atmospheric temperatures resulting from increased solar flux overshadow the heating influence of MSW dumps. The low correlation coefficients in other seasons reflect the influence of extraneous variables that weaken the influence of MSW heating effect, which largely controls the extents of thermal and biological hazardous influence zones around the dumping sites. Hence, it can be concluded that Spring is the optimal season for the study of bio-thermal characteristics of uncontrolled openly dumped waste, followed by Winter I.

This entire graphical and statistical analysis suggests that ignoring certain seasonal and extraneous variable effects, the extents of thermal and biological influence zones are highly correlated and are dependent upon the rate of biological and chemical degradation of waste in the central MSW dumps. Moreover, the significance of choosing the correct season in studying bio-thermal influences of municipal open dumps is depicted from the correlation analysis.

3.2. Relation between intensity and range of bio-thermal influence

Another interesting fact uncovered as a result of this study is the inverse relationship between the average max-min value of bio-thermal indicators and the extent of hazardous influence zone in each season (Figures 8 and 9). Since the max-min gap of a bio-thermal indicator is a measure of the severity of hazardous influence of the source, the possible explanation for such behaviour is meteorological conditions which enhance the max-min difference and exacerbate the rate of decomposition at the central source, causing the thermal and gaseous emissions to be released in large magnitude whilst simultaneously creating favourable conditions for nourishing healthy vegetation. The collective effect of it is that invigorated vegetation can depict the destructing influence of hazardous emissions at a much smaller radial distance than otherwise. Hence, an inverse relationship is seen between the average max-min
value of bio-influence and thermal indicators and the extent of hazardous influence zone around the dumping sites.

4. Conclusions

This study uses a combination of satellite remote sensing and GIS techniques to effectively monitor the collective bio-thermal influence of twin MSW dumping sites in Faisalabad. The results from prior researches about the spatial behaviour of bio-thermal influence of MSW dumps have been verified through this study. Meanwhile, certain interesting facts related to the seasonal and average yearly behaviour of bio-thermal influence of these dumping sites were uncovered. The average influence zone of all VIs for all four seasons is 747 m in 2016, 729.33 m in 2017, 699.66 m in 2018 and 644.33 m in 2019. In the same manner, the collective average influence zone of VIs for 4 years is 411, 607, 963.66, 668.33, 767 and 859.33 m in Winter I, Spring, Dry Summer, Monsoon, Wet Summer and Winter II, respectively. The average radial extent of the thermal-influence zone as calculated from distance dependent LST profiles is 1020, 883, 1146 and 1092 m in 2016, 2017, 2018, and 2019, respectively. The 4-year seasonal average thermal-influence zone is 688 m in Winter I, 768 m in Spring, 1025 m in Dry Summer, 840 m in Monsoon, 1013 m in Wet Summer and 913 m in Winter II.

It has been established from satellite data spanning over 4 years that owing to the chief common cause controlling the radial extents of thermal-influence and bio-influence zones, that is the biological and chemical degradation of solid waste, both these influence zones follow near similar temporal patterns. In fact, the degree of correlation is very high amongst the extents of hazardous thermal-influence and bio-influence zones averaged over a 4-year period, given by correlation coefficient of 0.9147 and an $R^2$ squared coefficient of 0.837. It has also been concluded that certain seasons i.e. Spring and Winter I, are more favourable to study and observe the exclusive bio-

![Figure 9. Intensity range relationship of thermal influence.](image-url)
thermal influence of MSW open dumps, since the overshadowing effect of other intervening variables is less in these seasons. The data also demonstrates an inverse relationship between the average seasonal max-min value of bio-thermal indicators and the corresponding extent of hazardous influence zone, demonstrating the ability of healthier vegetation to depict vegetation health changes efficiently. The developed method is sensitive enough to highlight unevenly distributed thermal and vegetation health controls around the dumps through significant variation in the bio-thermal continuum.

Overall, this study emphasizes the usefulness of integration of RS data with GIS techniques in developing a framework for environmental impact assessment of openly dumped MSW to devise sustainable waste management solutions for developing countries that suffer from weak monitoring and mitigation infrastructures. However, the synergistic use of high spatial resolution satellite datasets and ground sampled data can be further employed to enhance the accuracy of risk assessment of the hazardous bio-thermal influence of MSW open dumps, and constitutes the scope for future studies.

Data availability statement (DAS)

All the satellite data used in the research can be found at https://earthexplorer.usgs.gov/. Index reference of used images has been provided in the methodology section and corresponding dates in Table 2. Moreover, the outcomes of processing data have been provided in the paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

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