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Research Article

Analyzing solid waste landfills using satellite imagery and designing new landfill reception areas

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Abstract

Solid waste disposal is important for environmental management for good quality of life in urban cities. Among them is the final disposal of waste in landfills. Landfills can receive tons of waste, but they must be far away from natural resources and urban areas. The research aimed to analyze the physical and biological conditions and design a geolocation map of new sanitary landfills in three urban cities in Peru (Chilca, El Tambo and Huancayo). Landsat 8 OLI/TIRS satellite imagery was used to analyze the physical (LST and Methane) and biological (NDVI and SAVI) conditions of the landfills. The geolocation of the landfills was analyzed through the relationship, intersection and discrimination between their surface criteria (soil type, current use, geology and physiography) and climatic factors (temperature, humidity and precipitation). The physical and biological conditions of the landfills were: CH_4: Chilca 8.33g > Huancayo 4.76g > El-Tambo 3.17g; SAVI: Chilca 0.61 > El Tambo 0.54 > Huancayo 0.51; LST: Huancayo 26.15°C > Chilca 24.03°C > El Tambo 22.75°C; NDVI: Chilca 0.85 > Huancayo 0.81 > El Tambo 0.8. In the three cities, "natural grasslands" were considered suitable land for the new solid waste landfill site. The multiple relationship, intersection, and discrimination of surface criteria and climatic factors were categorized into five types of sustainable geolocation (very appropriate > appropriate > moderately adequate > less appropriate > inappropriate) for new solid waste landfills. It was very important to discount the influence areas (rivers and lagoons) to avoid damaging the natural resources.

Keywords: Geolocation of new landfills, Methane, Normalized difference vegetation index (NDVI), Soil-adjusted vegetation index (SAVI), Temperature

INTRODUCTION

Accelerated population growth, urban connections, economic growth and quality of life standards have lightened the solid waste generation process (David *et al.*, 2020; Qureshi *et al.*, 2021; Sernaque and Auccahuasi, 2020). Many people claim that being in the presence of solid waste landfills is very uncomfortable (Ekeu-wei *et al.*, 2018; Jinadasa *et al.*, 2015; Sadeghi-Niaraki *et al.*, 2020; Yang *et al.*, 2019). Because landfills bring with them many factors that put public health, environmental impact (Abu and Shatnawi, 2019; Devesa and Brust, 2021; Vaverková, 2019) and the quality of life of the inhabitants at risk (Mussa and Suryabhagavan, 2021;

Vaverková, 2019). Solid waste management is a problem faced by many countries (Iran (Shahabi *et al*., 2014), Republic of Liberia (David *et al*., 2020), Rawalpindi City of Pakistan (Ejaz *et al*., 2010) and Yenagoa of Nigeria (Ekeu-wei *et al*., 2018)). This involves and integrates a series of activities such as collection, treatment, storage, transportation, monitoring, disposal, etc. (David *et al*., 2020; Ekeu-wei *et al*., 2018; Inglezakis *et al*., 2018; Mussa and Suryabhagavan, 2021). Many urban cities such as Al-Hashimeyah of Jordania (Abu and Shatnawi, 2019), Semnan province of Iran (Shahabi *et al*., 2014), Lahore district of Pakistan (Mahmood *et al*., 2016) and Afar region of Ethiopia (Mussa and Suryabhagavan, 2021)) have indicated that landfills are an alternative to manage waste sustainably (Azmi *et al*., 2020; Devesa and Brust, 2021; Guimarães *et al*., 2019; Vaverková, 2019). Likewise, Environmental Authorities are making efforts to propose adequate stockpiles and landfills for solid waste management (Шевякіна *et al*., 2019), choosing a desolate area with previous studies (physical, chemical and biological soil, hydrological properties and its radius of influence) for total solid waste disposal (Devesa and Brust, 2021; Ottavianelli *et al*., 2005). But unfortunately, due to the high cost of these studies, it is impossible to identify sustainable solutions for solid waste disposal (Qureshi *et al*., 2021; Vaverková, 2019).

Sustainable geolocation of sites suitable for solid waste disposal should be located away from natural environmental resources, residential areas, water bodies, roads and human settlements (Devesa and Brust, 2021; Richter *et al*., 2017; Sadeghi-Niaraki *et al*., 2020). Countries around the world have successfully applied GIS, remote sensing and spectral bands for urban waste planning and management (Krishna *et al*., 2017; Shahabi *et al*., 2014). The advantage of sustainable site selection for solid waste with a GIS-based approach is saving time and costs (Richter *et al*., 2017; Shahabi *et al*., 2014; Шевякіна *et al*., 2019). GIS and spectral bands can analyse spatiotemporal data to obtain accurate information on various criteria influencing landfill selection (Shahabi *et al*., 2014; Shaker and Yan, 2010; Yang *et al*., 2019). Although such a ground-based monitoring scheme is useful and accurate, it requires intensive effort to examine and monitor the impact over a large geographic area (Abu and Shatnawi, 2019; Aderoju *et al*., 2018; Shevchuk *et al*., 2021). Thus, the application of remote sensing has become a feasible and cost-effective solution for monitoring, detecting and analysing the spatial and temporal extent and changes of landfills (Mahmood *et al*., 2016; Mussa and Suryabhagavan, 2021).

The geolocation of a sustainable area for new solid waste landfills depends on a large amount of geographic information on land use, urban areas, road network, geology, hydrology, etc. (Mahmood *et al*., 2016; Shevchuk *et al*., 2021; Yan *et al*., 2014). The use of Landsat satellite imagery, edaphic and environmental surface types could be used as a cost-effective and extensive method to study the geolocation of landfills (Mahmood *et al*., 2016), as well as to evaluate their physical and biological parameters (Agarwal and Garg, 2009; Gill *et al*., 2019; Mahmood *et al*., 2016; Nazari *et al*., 2020). Assessing temperature and methane individually in landfills can generate contamination radii (Al-Hanbali *et al*., 2011; Mahmood *et al*., 2016; W. Sun *et al*., 2019; Vaverková, 2019; Yan *et al*., 2014). Estimating their degraded area, influence and state of soil and plant health is very important for selecting the geolocation of solid waste landfills (Ekeu-wei *et al*., 2018; Mahmood *et al*., 2016; Sadeghi-Niaraki *et al*., 2020). Then GIS can help to overlay all geographic data to select an optimal area (Al-Hanbali *et al*., 2011; Mussa and Suryabhagavan, 2021; Qureshi *et al*., 2021; Shahabi *et al*., 2014; Shaker and Yan, 2010). Therefore, this research aimed to analyse the physical and biological environment of three landfills (Chilca, El Tambo and Huancayo of Peru), and designed new sustainable geolocation areas for new solid waste landfills.

MATERIALS AND METHODS

Location of solid waste landfills

Three landfills- Ubication in Chilca, El Tambo and Huancayo of Peru were studied. These landfills have something in common; the "urban boundary connections" between the districts of Chilca, El Tambo and Huancayo (Fig. 1).

Data collection techniques and instrument

Solid waste landfills were analysed using Landsat 8 OLI/TIRS satellite images from the United States Geological Survey (USGS) (characteristics of the bands: date July 8, 2021; data LC08 L1TP 006068 20210701 20210708 02 T1; 0% cloudiness; path 6 row 68; bands TIR 1,2, Green, Red, NIR). The physical (temperature ° C and methane emission) and biological (NDVI and SAVI) environments were determined within their 1km radius of influence(applying the geometric and radiometric corrections to each multispectral band using the ArcGIS V. 10.5 geostatistics software.

$$\mathrm{L\lambda = ML * Qcal + AL} \quad \text{(Eq. 1)}$$

$$\mathrm{p\lambda} = \frac{\mathrm{Mp{*}Qcal + Ap}}{\cos[\theta_{\mathrm{ZE}}]} \quad \text{(Eq. 2)}$$

Where: Lλ: TOA spectral radiance (watts/(m^2*sr*mm)). ML: multiplicative band radiance. AL: band radiance. Qcal: pixel value of calibrated quantized standard products. Equation (2): ρλ: TOA reflectance of the sensor, corrected by the solar angle. Qcal: calibrated quantified standard pixel product (ND) value. Mρ: multiplicative scale factor. Aρ: additive band-specific scale change factor of the metadata. θ_{ZE}: Local Sun Elevation Angle ($90-\theta_{ZE}$, θ_{ZE} solar elevation) (Ekeu-wei *et al.*, 2018).

$$T = \frac{T_b}{1+\left[\frac{\lambda T_b}{d}\right]*\ln[e]} \qquad \text{(Eq. 3)}$$

$$T_b = \frac{K_2}{\ln\left[\frac{K_1*e'}{L_\lambda}+1\right]} - 273.15 \qquad \text{(Eq. 4)}$$

$$e = 0.004 + 0.986 * P_v \qquad \text{(Eq. 5)}$$

$$P_v = \left[\frac{NDVI-NDVI_{min}}{NDVI_{max}-NDVI_{max}}\right]^2 \qquad \text{(Eq. 6)}$$

Where: T: land surface temperature (LST °C). Tb: blackbody temperature. λ: wavelength of the emitted radiation, d: defined by d=ch/kB, speed of light (c=3*108 m/s) is multiplied by Planck's constant (h=6.26*10-34 J.s) and divided by Boltzmann's constant (kB = 1.38*10-23 J/K). K1 y K2: thermal constant of the TIR band. e': emissivity of the earth's surface (Abu and Shatnawi, 2019; Nazari *et al.*, 2020). NDVI: normalized difference vegetation index (maximum and minimum).

$$E_{CH4} = E_{obs} * F_t * A \qquad \text{(Eq. 7)}$$

$$F_t = \frac{F[T_S]}{\overline{F[Ts]}} \qquad \text{(Eq. 8)}$$

$$F[T_s] = \frac{e^{0.334*[T_S-23]}}{1+e^{0.334*[T_S-23]}} \qquad \text{(Eq. 9)}$$

Where: Eobs: observed methane flux of different classes (g/m^2). F1: Temperature factor inside solid waste landfills. A: landfill area (m^2). The observed methane fluxes for all classes have been used based on the analysis monitored in the field. F[Ts]: temperature factor. F[Ts] was calculated from spectral bands. ($\overline{F[T_S]}$): mean temperature. Ts: land surface temperature (Agarwal and Garg, 2009; Akumu *et al.*, 2010). A semi-automated procedure was developed and used that incorporated the steps necessary to estimate methane using Landsat data (Abu and Shatnawi, 2019; Devesa and Brust, 2021). The coefficients of this exponential equation were taken from recent literature (Sun *et al.*, 2017).

$$NDVI = \left[\frac{NIR-RED}{NIR+RED}\right] \qquad \text{(Eq. 10)}$$

$$SAVI = \frac{NIR-RED}{[NIR+RED+L]} * [1 + L] \qquad \text{(Eq. 11)}$$

Where: NIR: near-infrared band, RED: red band, L: ground brightness correction factor. L varies according to the amount of cover of vegetation. Original formulas of Huete, (1988) and Rouse *et al.*, (1974).

Developed geolocation

Geolocation for the new landfill was developed by map mask relation, intersection and discrimination (Gill *et al.*, 2019; Mussa and Suryabhagavan, 2021): geological data (geology, physiography, soil type), climate (temperature, precipitation, humidity; data dated July 8, 2021) and superficial (current use of district space). Each geographic space was discriminated according to its physical and environmental characteristics and optimal conditions for the new landfill (Gill *et al.*, 2019; Mussa and Suryabhagavan, 2021; Vishnuvardhan and Elangovan, 2020). The areas (radius) of influence that had rivers (100m) and lakes (300m) as natural resources were subtracted (Krishna *et al.*, 2017; Mahmood *et al.*, 2016) (basic criteria for the selection of new landfills by WHO) (Sadeghi-Niaraki *et al.*, 2020) (Using the ArcGis Buffer Tool). Gill *et al.*, (2019) represented a mathematical model of the relationship and intersection between the LST and the precise location of a landfill. Although his model did not consider multiple surface edaphic and climatic criteria. However, this model served as a guide for the geolocation of the new landfill for the cities of Chilca, Huancayo and El Tambo.

$$\bigcap_{t=1}^{T} C'_t = C'_1 \cap C'_2 \cap \ldots \cap C'_T \Rightarrow P\left(\frac{C}{W}\right)$$

Where: C: LST contour, W: landfill location, C: temporal contours, T: temporal time, P(C|W): the probability that the contour corresponds in the landfill area (Gill *et al.*, 2019).

RESULTS AND DISCUSSION

Landfill methane and temperature records

Among the different indicators analysed and determined within the landfills: temperature, methane (physical parameters), vegetation health and soil erosion as a function of vegetation (biological parameters), methane (CH4) emission was the first and most important parameter to be determined at each solid waste landfill. The methane concentration was determined on 2021/07/08, representing methane concentration in a day, not a year or month. The methane concentrations in the landfills were: Chilca 8.33 g > Huancayo 4.76 g > El Tambo 3.17 g. The maximum landfill temperatures within 1km area of influence were: Huancayo 26.15°C > Chilca 24.03°C > El Tambo 22.75°C. The radius of influence generated by the landfills on NDVI and SAVI was compared with their detrimental impacts because it was preferable to analyze the consequences that were produced. In $NDVI^-$ the impact of landfills was as follows: "Chilca" = "Huancayo" -0.71 > -0.46 "El Tambo" (vegetation is definitely damaged in Chilca and Huancayo). In $SAVI^-$ "Chilca" = "Huancayo" -0.11 > -0.09 "El Tambo" (likewise soil erosion as a function of vegetation is less damaged in Chilca) (Fig. 2).

The selection of a satellite image indicated precisely the actual and current state of the monitoring point. Then, estimating methane, temperature, NDVI and SAVI for a single time did not mean that the solid waste landfills presented in those conditions. That is why Akumu *et al*., (2010); Sun *et al*. (2017) and Tello *et al*. (2020) suggest a temporal evaluation to affirm the current situation that the landfills presented. Analyzing the state of landfills temporally is more efficient and effective in determining their direct radius of influence. Although it must consider that a good image with 0% cloud cover is one factor that influences the processing of spectral bands. The present study also demonstrated that all the parameters (physical and biological) evaluated have different response values in different landfill areas.

Vegetation health is one of many influences that solid waste landfills can affect within 1 km of influence. The health of the landfills in Chilca, Huancayo and El Tambo was found to be in good vegetative condition. However, it was also affected by the landfills (as seen in the negative digital values). This meant that the solid waste landfills had damaged the state of the vegetation within 1 km of influence. Soil erosion as a function of vegetation was influenced by landfills, due to the use of heavy machinery (excavators, soil compactors) extracting tons of soil to cover solid waste (being an indirect assessment effect). The solid waste landfills located in the cities of Chilca and Huancayo showed more soil erosion than the city of El Tambo.

Geolocation of new solid waste landfills

Designing a geolocation area for new municipal solid waste landfills in three cities was the most important objective of the research. Previously, landfills' biological and physical impacts in a radius of influence were analyzed. These data were important to consider what criteria on-site landfills need for sustainable geolocation. The landfill geolocation was determined by basic discrimination criteria: "physical soil characteristics and climatic variables by city".

Prime current landfill analysis: Current city landfill [current management by environmental authorities] was related to their areas of influence [physical (ph) // biological (bi) // urban area (ua) // hydrography (hy) // climate (cl) // among others parameters (α)], as shown in equation 13.

$$\mathrm{Lcu}_{\forall i=1,2,3,\ldots,n} \cup \mathrm{A}\emptyset_{i=k} \in \mathrm{K}[\mathrm{ph}_{i=1}^{n} \cup \mathrm{bi}_{i=1}^{n} \cup \mathrm{ua}_{i=1}^{n} \cup \mathrm{hy}_{i=1}^{n} \cup \mathrm{cl}_{i=1}^{n} \cup \alpha_{i=1}^{n}] \quad \text{(Eq. 13)}$$

Where: Lcu: landfill current use; □i=1,2, 3, …, n: for any city; A□: area of influence; K: multiple criteria. The basic considerations mentioned in the first analysis were important to differentiate the area of influence in the physical, biological, hydrographic, climatic and urban environments. These criteria were valuable for each city's sustainable geolocation of solid waste landfill.

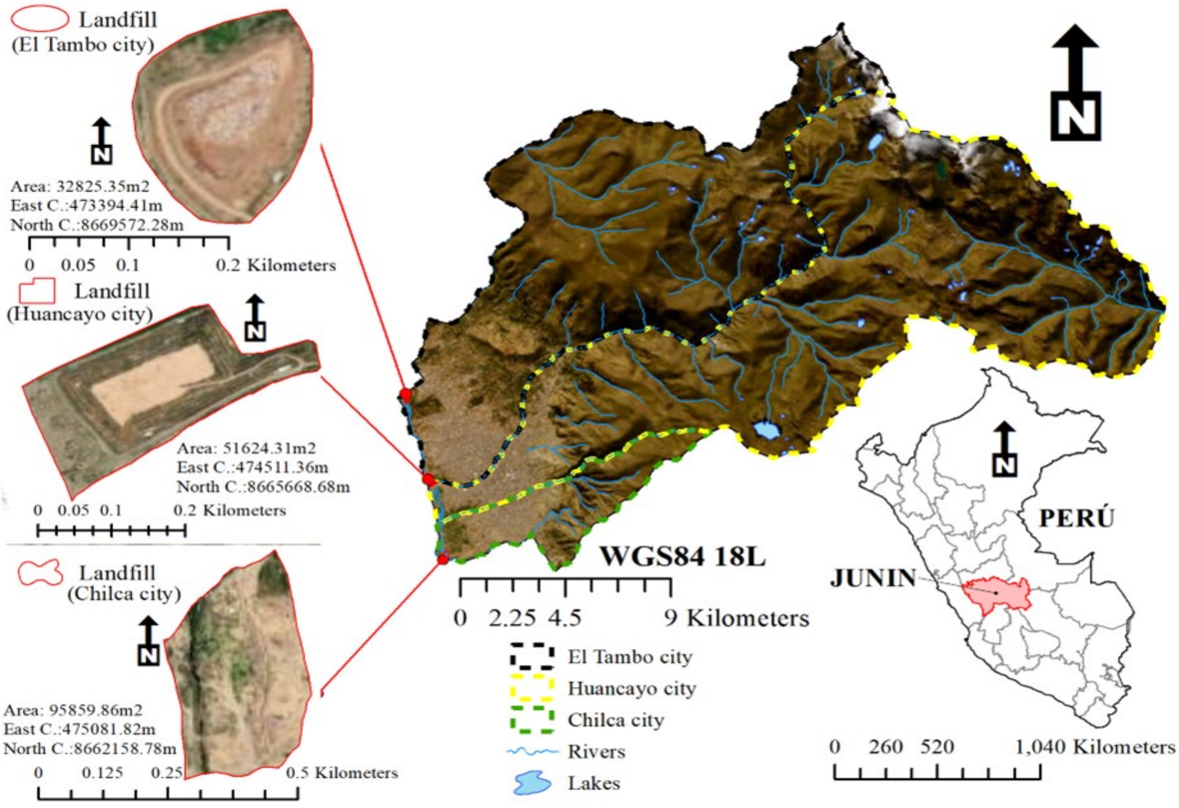

Fig. 1. *Location map of solid waste landfills in Chilca, Huancayo and El Tambo - Peru. Landfills were in contact with urban and agricultural areas, roads, rivers and forests*

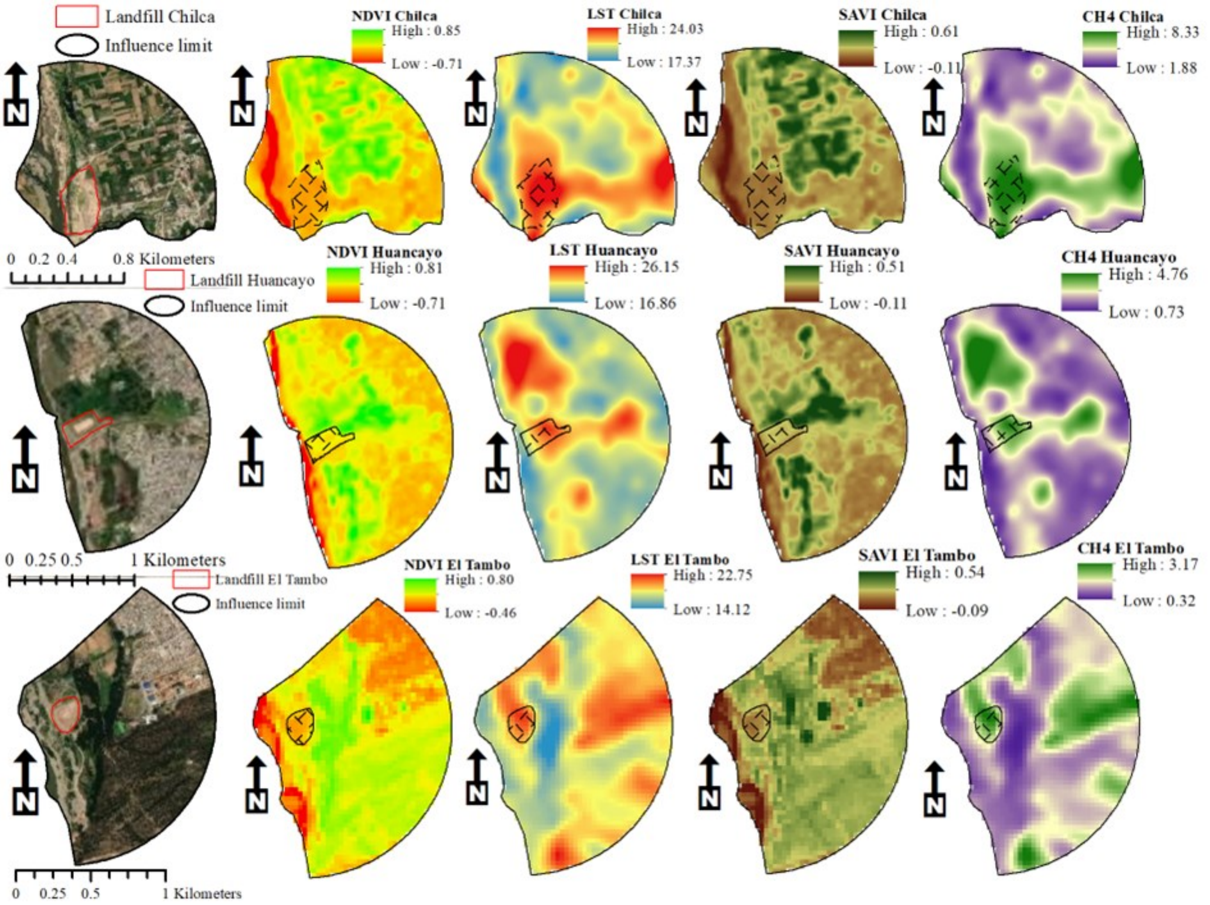

Fig. 2. *Physical and biological parameters of landfills (Note: Influence of the landfills affected a 1-kilometer distance between urban areas, water resources, soil and vegetation. All landfills had an influence on urban areas, water resources and green areas. Huancayo and El Tambo had intra-district landfill boundary connections)*

The research sources used the multi-criteria decision analytic processes: analytic hierarchy process (AHP) and weighted linear combination (WLC). Al-Hanbali *et al*., (2011) and Vishnuvardhan and Elangovan, (2020) used WLC while Kabite etal., (2012); Mussa and Suryabhagavan, (2021) and Shahabi *et al*., (2014) used both. Both methods were easy for him to identify the landfill surface. However, we know that AHP groups mathematical and psychological criteria in its analysis while WLC assigns weights. In the mathematical part (AHP) we ensured that the criteria of "relation, intersection and discrimination" were included for the geolocation of landfills; but in the psychological part it is not a good indicator for the geolocation of landfills. It is knownn that the attitudinal or psychological options and weighted weights (WLC) are not enough to select the right area for the new landfill reception. That is why the first analysis had to be corrected.

Second analysis: The current surface conditions of each city and its area of influence were considered. The new landfill < interaction and radius of influence [current usage (cu) // geology (ge) // physiography (py) // soil type (st) // temperature (t) // precipitation (p) // humidity (h)], as shown in equation 14.

$$\mathrm{Lcu}_{\forall i=1,2,3,\ldots,n}^{\mathrm{new}} < \mathrm{A}\emptyset||\forall_{\mathrm{K-new}} \leftrightarrow \mathrm{City}[\cancel{\mathrm{cu}_{i=1}^{n}} \cap \mathrm{ge}_{i=1}^{n} \cap \mathrm{py}_{i=1}^{n} \cap \mathrm{st}_{i=1}^{n} \cap \mathrm{t}_{i=1}^{n} \cap \mathrm{p}_{i=1}^{n} \cap \mathrm{h}_{i=1}^{n}] \tag{14}$$

Where: $\mathrm{Lcu}_{\forall i=1,2,3,\ldots,n}^{\mathrm{new}}$: new landfill for each city; □K-new: for new criteria. The current land use was considered unsuitable for the new solid waste landfill. Implementing new criteria determined that the "natural pastures" were found to be in the initial position for disposal and geolocation of the new landfill for each respective city.

To design a new landfill geolocation, one must use all environmental scenarios that influence in situ. No! as Gill *et al*. (2019) only used temporal analysis of temperature to identify the new landfill. Therefore, 8 environmental criteria had to be used (to more as suggested by Kabite *et al*., (2012); and Mussa and Suryabhagavan (2021)) as shown in Fig. 3, although these criteria were lower than Shahabi *et al*., (2014), even though the geolocation of the new solid waste landfill was determined for each city as described in the third analysis.

Third analysis: After choosing natural pastures, all environmental surface criteria (geology, physiography, soil type, temperature, precipitation and humidity) required by the landfills were analyzed. The selection followed did not involve having an order of evaluation by criteria, it only involved analyzing their environmental surfaces and their radius of influence. The physiography, geology and soil type of the soil can have a simple classification up to multiple classifications. For example, where high hills, sandy-gritty loam, sand and clay < were less chosen by < low hills, sandy clay loam, clay silt and sand for landfills. Successively, the inner classifications within the soil surface were discriminated against until the sustainable geolocation of new solid waste landfills was reached (Fig. 3).

The model of relationship, intersection and discrimination between the multiple criteria was realized in equa-

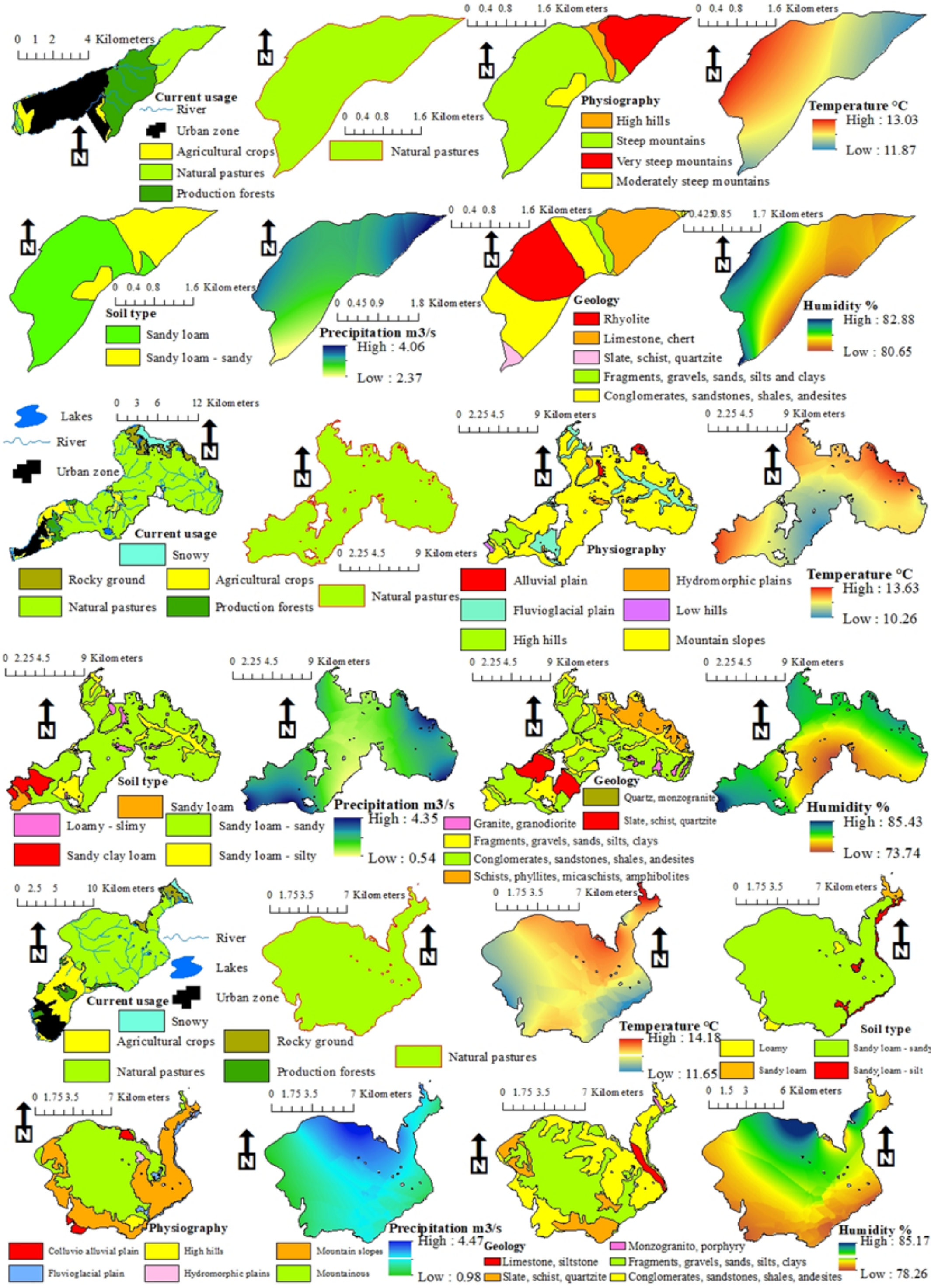

Fig. 3. *Selection of edaphic and climatic surfaces for intersection and discrimination (Note: The discriminatory process of soil and climatic conditions was analyzed under the basic criteria required for new landfills. The procedure started with the selection of natural pastures. Followed by the interior classifications applied in the rest of the areas)*

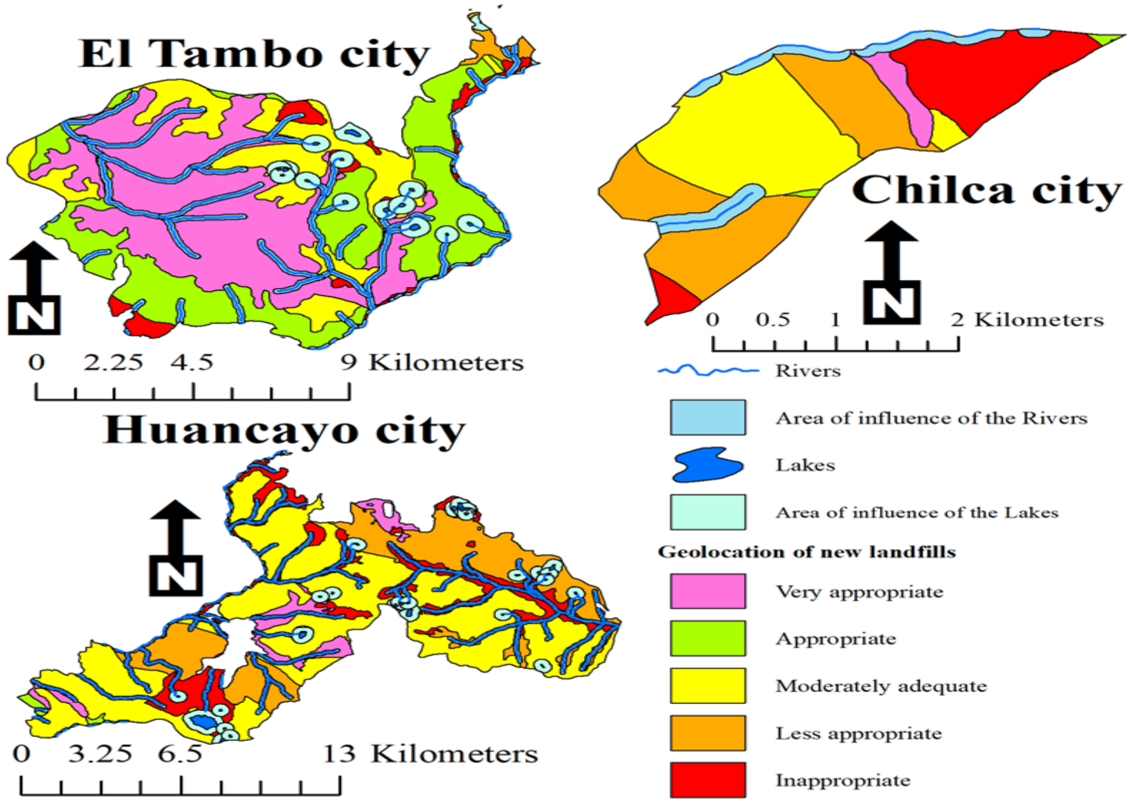

Fig. 4. *Geolocation of the new landfill (GNL) for the districts of Chilca, El Tambo, and Huancayo. {Note: The new areas were ranked at five responses for new solid waste landfills. Due to water interactions with the GNL, the areas of influence were determined (rivers 100 m and lakes 300 m). The maximum value |SLSWL| - A□ → applied to the five areas [Vap, App, Mad, Lap, Ina]}*

tion 15:

$$\bigcap_{\forall i=1\ldots n}^{\text{new A}} GNL_{i=1}^{\beta x} = Np_{i=1}^{\beta x} \cap Ge_{i=1}^{\beta x} \cap St_{i=1}^{\beta x} \cap Ph_{i=1}^{\beta x} \cap t_{i=1}^{\beta x} \cap p_{i=1}^{\beta x} \cap h_{i=1}^{\beta x} + \alpha_{i=1}^{\beta x} \Rightarrow P\left[|GNL| - A\emptyset_{i=1}^{\beta x}\right] \quad (15)$$

Where: GNL: Geolocation of New Landfill; new A: new area; ∀i=1…n: for each city; βx: multiple classification criteria (For example, physiography of Huancayo: alluvial plain, fluvioglacial plain, high hills, hydromorphic plains, low hills, mountain slopes); Np: natural pastures; Ge: geological; St: soil type; Ph: physiographic; t: temperature; p: precipitation; h: humidity; α: other parameters to be considered in the future; P [...]: final product; |GNL|: maximum allowable value of the landfill area; A□: radius or area of influence [□ river=100 m; □ lake= 300 m]. The geolocation surfaces of the new landfill for each city can be seen in Table 1.

Fourth analysis |GNL| was considered as the absolute value of the new landfill which was to be subtracted with its radius of influence " $A\emptyset^{\beta x}$ " (sum of rivers and lakes). Rivers and lagoons have an influence value that was subtracted for each evaluation criterion. For example, Al-Hanbali *et al*. (2011), Krishna *et al*. (2017) and Mahmood *et al*. (2016) used "Buffer (Geoprocessing in ArcGIS)" to distance the new landfill, but did not use it for natural resources that may be exposed to the radius of influence of the landfill. Therefore, the "Buffer" was used to determine the area of influence of the rivers and lakes on the impact of the new solid waste landfill. Each city presented different areas suitable for the new landfill. Five geolocations for new solid waste landfills were ranked. The first three, "Very appropriate, Appropriate, Moderately adequate" represented better options for new landfills due to their better edaphological and climatic quality. While the remaining two, "Less appropriate, Inappropriate", were not considered for landfills due to the above conditions. The cities that had more water surfaces presented more areas of influence and the result of these areas was reduced to the five geolocation criteria (Fig. 4).

Conclusion

The Chilca, El Tambo and Huancayo landfills presented a direct influence radius (1 km) on their biological and physical states. The landfills presented high methane concentration, temperature and soil erosion as a function of vegetation and vegetation health. The natural pastures of each city were one of the most important surface soil criteria to start the search for the new landfill. The relationship, intersection and discrimination of

Table 1. Surfaces divided into five categories for the Geolocation of New Landfills (GNL)

GNL	Huancayo city			El Tambo city			Chilca city		
	|GNL|	$A\emptyset^{\beta x}$	$\cap\ \mathrm{GNL}^{\mathrm{newA}}$	|GNL|	$A\emptyset^{\beta x}$	$\cap\ \mathrm{GNL}^{\mathrm{newA}}$	|GNL|	$A\emptyset^{\beta x}$	$\cap\ \mathrm{GNL}^{\mathrm{newA}}$
Vap	8.95	1.8	7.15	45.39	7.35	38.04	0.25	0.04	0.21
App	0.96	0.16	0.8	35.25	3.96	31.29	0.04	-	0.04^{x}
Mad	88.68	10.23	78.45	20.54	3.49	17.05	2.01	0.15	1.86
Lap	39.74	7.31	32.42	1.6	0.33	1.28	2.21	0.39	1.83
Ina	29.44	20.87	8.57	6.33	2.4	3.93	1.34	0.22	1.12
Total	167.76	40.37	127.39	109.11	17.52	91.6	5.86	0.8	5.06

Surfaces in km^2. x: the surface did not reach the current state of the landfill; Vap: Very appropriate; App: Appropriate; Mad: Moderately adequate; Lap: Less appropriate; Ina: Inappropriate.

the multiple edaphic and climatic surface criteria presented by the surfaces "in the function of natural pastures" were important for selecting the new landfill. It was very important to subtract the areas of influence of the water resources that interacted with geolocations for the new landfills to solve the solid waste problem.

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Conflict of interest

The authors declare that they have no conflict of interest.

REFERENCES

1. Abu, H. & Shatnawi, N. (2019). Assessing and predicting landfill surface temperature using remote sensing and an artificial neural network. *International Journal of Remote Sensing*, *40*(24), 1–17. https://doi.org/10.1080/01431161.2019.1633703
2. Aderoju, O. M., Dias, G. A. & Alberto, G. J. (2018). A spaced-based concept in municipal solid waste management and monitoring in developing countries. *International Journal of Environmental Impacts: Management, Mitigation and Recovery*, *1*(4), 482–490. https://doi.org/10.2495/ei-v1-n4-482-490
3. Agarwal, R. & Garg, J. K. (2009). Methane emission modelling from wetlands and waterlogged areas using MODIS data. *Current Science Association*, *96*(1), 36–40.
4. Akumu, C. E., Pathirana, S., Baban, S. & Bucher, D. (2010). Modeling methane emission from wetlands in North-Eastern New South Wales, Australia using Landsat ETM+. *Remote Sensing*, *2*(5), 1378–1399. https://doi.org/10.3390/rs2051378
5. Al-Hanbali, A., Alsaaideh, B. & Kondoh, A. (2011). Using GIS-Based weighted linear combination analysis and remote sensing techniques to select optimum solid waste disposal sites within Mafraq City, Jordan. *Journal of Geographic Information System*, *03*(04), 267–278. https://doi.org/10.4236/jgis.2011.34023
6. Azmi, M. Z. M., Mohamad Sharom, M. A. A., Md Zin, S. M., Numpang, W. & Sipit, C. A. R. (2020). Suspected unregulated dumping site detection and verification using high resolution satellite images and drone full motion video (FMV) data. *ACRS 2020 - 41st Asian Conference on Remote Sensing*, *2*(4), 1–10.
7. David, V. E., John, Y. & Hussain, S. (2020). Rethinking sustainability: a review of Liberia's municipal solid waste management systems, status, and challenges. *Journal of Material Cycles and Waste Management*, *22*(5), 1299–1317. https://doi.org/10.1007/s10163-020-01046-x
8. Devesa, M. & Brust, A. (2021). Mapping illegal waste dumping sites with neural-network classification of satellite imagery. *KDD Humanitarian MappingWorkshop - Cornell University*, *1*(2), 14–18. https://doi.org/10.48550/arXiv.2110.08599
9. Ejaz, N., Akhtar, N., Nisar, H. & Ali Naeem, U. (2010). Environmental impacts of improper solid waste management in developing countries: A case study of Rawalpindi City. *WIT Transactions on Ecology and the Environment*, *142*(2), 379–387. https://doi.org/10.2495/SW100351
10. Ekeu-wei, I. T., Azuma, K. I. & Ogunmuyiwa, F. B. B. (2018). Assessment of environmental impact of solid waste dumpsites using remote sensing. *Nigerian Journal of Technology*, *37*(1), 275–286. https://doi.org/10.4314/njt.v37i1.36
11. Gill, J., Faisal, K., Shaker, A. & Yan, W. Y. (2019). Detection of waste dumping locations in landfill using multi-temporal Landsat thermal images. *Waste Management and Research*, *37*(4), 386–393. https://doi.org/10.1177/0734242X18821808
12. Guimarães, C. C., Barbosa, A. M. & Gandolfo, O. C. B. (2019). Visual interpretation of satellite and aerial images to identify and study the evolution of inadequate urban waste disposal sites. *Detritus - Multidisciplinary Journal for Waste Resources and Residues*, *6*(June), 85–95. https://doi.org/10.31025/2611-4135/2019.13821
13. Huete, A. R. (1988). A Soil-Adjusted Vegetation Index (SAVI). *Remote Sensing of Environment*, *25*(1), 295–309. https://doi.org/10.1016/0034-4257(88)90106-X
14. Inglezakis, V. J., Moustakas, K., Khamitova, G., Tokmurzin, D., Sarbassov, Y., Rakhmatulina, R., Serik, B., Abikak, Y. & Poulopoulos, S. G. (2018). Current municipal

solid waste management in the cities of Astana and Almaty of Kazakhstan and evaluation of alternative management scenarios. *Clean Technologies and Environmental Policy*, *20*(3), 503–516. https://doi.org/10.1007/s10098-018-1502-x

15. Jinadasa, A. R. P., Munasinghe, M., Pathirana, P., Perera, W., Sandamalee, B., Sandamalee, B., Wickramasinghe, A., Wijekoon, T. M. P. & Mubeenudeen, M. M. M. (2015). Design an Effective Solid Waste Management Model for Sri Lankan Context. *University of Kelaniya - Sri Lanka*, *2* (4), 1–20.
16. Kabite, G., Suryabhagavan, K. V. & Sulaiman, H. (2012). GIS-Based Solid Waste Landfill Site Selection in Addis Ababa, Ethiopia. *International Journal of Ecology and Environmental Sciences*, *38*(3), 59–72.
17. Krishna, V., Pandey, K. & Karnatak, H. (2017). Geospatial multicriteria approach for solid waste disposal site selection in Dehradun city, India. *Current Science*, *112*(3), 549–559. https://doi.org/10.18520/cs/v112/i03/549-559
18. Mahmood, K., Adila, S. & Nawaz, M. (2016). Studying biothermal effects at and around MSW dumps using Satellite Remote Sensing and GIS. *Waste Management*, *4*(2), 1–11. https://doi.org/10.1016/j.wasman.2016.04.020
19. Mussa, A. & Suryabhagavan, K. V. (2021). Solid waste dumping site selection using GIS-based multi-criteria spatial modeling: a case study in Logia town, Afar region, Ethiopia. *Geology, Ecology, and Landscapes*, *5*(3), 1–13. https://doi.org/10.1080/24749508.2019.1703311
20. Nazari, R., Alfergani, H., Haas, F., Karimi, M. E., Fahad, M. G. R., Sabrin, S., Everett, J., Bouaynaya, N. & Peters, R. W. (2020). Application of satellite remote sensing in monitoring elevated internal temperatures of landfills. *Applied Sciences (Switzerland)*, *10*(19), 1–20. https://doi.org/10.3390/app10196801
21. Ottavianelli, G., Hobbs, S., Smith, R. & Bruno, D. (2005). Assessment of hyperspectral and SAR remote sensing for solid waste landfill management. *European Space Agency, (Special Publication) ESA SP*, *593*, 103–110.
22. Qureshi, S., Shorabeh, S. N., Samany, N. N., Minaei, F., Homaee, M., Nickravesh, F., Firozjaei, M. K. & Arsanjani, J. J. (2021). A new integrated approach for municipal landfill siting based on urban physical growth prediction: A case study mashhad metropolis in Iran. *Remote Sensing*, *13*(5), 1–22. https://doi.org/10.3390/rs13050949
23. Richter, A., Kazaryan, M., Shakhramanyan, M., Nedkov, R., Borisova, D., Stankova, N., Ivanova, I. & Zaharinova, M. (2017). Estimation of thermal characteristics of waste disposal sites using landsat satellite images. *Comptes Rendus de L'Academie Bulgare Des Sciences*, *70*(2), 253–262.
24. Rouse, J. W., Hass, R. H., Schell, J. A. & Deering, D. W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. *NASA. Goddard Space Flight Center 3d ERTS-1 Symp.*, *1*(A), 309–317. https://ntrs.nasa.gov/api/citations/19740022614/downloads/19740022614.pdf
25. Sadeghi-Niaraki, A., Jelokhani-Niaraki, M. & Choi, S. M. (2020). A volunteered geographic information-based environmental decision support system for waste management and decision making. *Sustainability (Switzerland)*, *12* (15), 1–21. https://doi.org/10.3390/su12156012
26. Sernaque, F. & Auccahuasi, W. (2020). Low-cost methodology for monitoring municipal land fills, based on the use of satellite images. *Palarch's Journal of Archaeology of Egypt/Egyptology*, *17*(6), 5591–5598.
27. Shahabi, H., Keihanfard, S., Ahmad, B. Bin & Amiri, M. J. T. (2014). Evaluating Boolean, AHP and WLC methods for the selection of waste landfill sites using GIS and satellite images. *Environmental Earth Sciences*, *71*(9), 4221–4233. https://doi.org/10.1007/s12665-013-2816-y
28. Shaker, A. & Yan, W. Y. (2010). Trail road landfill site monitoring using multioral landsat satellte data. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *38*(2), 1–6.
29. Shevchuk, O. V., Azimov, O. T. & Tomchenko, O. V. (2021). Remote sensing monitoring of the landfill sites as a factor of adverse environmental impact. *20th International Conference Geoinformatics: Theoretical and Applied Aspects*, *2*(May 2021), 1–7. https://doi.org/10.3997/2214-4609.20215521054
30. Sun, M., Zhang, Y., Ma, J., Yuan, W., Li, X. & Cheng, X. (2017). Satellite data based estimation of methane emissions from rice paddies in the Sanjiang Plain in northeast China. *PLoS ONE*, *12*(6), 1–16. https://doi.org/10.1371/journal.pone.0176765
31. Sun, W., Wang, X., DeCarolis, J. & Barlaz, M. (2019). Evaluation of optimal model parameters for prediction of methane generation from selected U.S. landfills. *Waste Management*, *91*, 120–127. https://doi.org/10.1016/j.wasman.2019.05.004
32. Tello Lozada, D., Peña Choco, K. T. & Hernández Torres, L. F. (2020). Estimation of methane emission (CH4) in the Presidente landfill through satellite images. *Revista de Topografía Azimut*, *11*(2), 11–17.
33. Vaverková, M. D. (2019). Landfill impacts on the environment— review. *Geosciences (Switzerland)*, *9*(10), 1–16. https://doi.org/10.3390/geosciences9100431
34. Vishnuvardhan, K. & Elangovan, K. (2020). Application of remote sensing and GIS for identifying suitable sites for solid waste disposal in Erode Corporation, Tamil Nadu, India. *Indian Journal of Geo-Marine Sciences*, *59*(9), 1479–1485.
35. Yan, W. Y., Mahendrarajah, P., Shaker, A., Faisal, K., Luong, R. & Al-Ahmad, M. (2014). Analysis of multitemporal landsat satellite images for monitoring land surface temperature of municipal solid waste disposal sites. *Environmental Monitoring and Assessment*, *186*(12), 8161–8173. https://doi.org/10.1007/s10661-014-3995-z
36. Yang, W., Fan, B. & Desouza, K. C. (2019). Spatial-temporal effect of household solid waste on illegal dumping. *Journal of Cleaner Production*, *227*, 313–324. https://doi.org/10.1016/j.jclepro.2019.04.173
37. Шевякіна, Н. А., Трофимчук, О. М., Клименко, В. І. & Красовський, Г. Я. (2019). Методи і моделі космічного моніторингу зон впливу полігонів твердих побутових відходів на довкілля. *Космическая Наука И Техника - Дослідження Землі з Космосу*, *25*(1), 62–72. https://doi.org/10.15407/knit2019.01.062