Review of vegetation indices for studies of post-mining processes

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Abstract. Each phenomenon has its cause and effect. During the research on the post-mining processes, the reasons can be found in ongoing processes taking place after the end of the mining exploitation. Therefore, a very important aspect is Geomonitoring. Currently, the post-mining processes taking place all over the world, should be considered into two groups of processes: such taking place in subsurface regions and such on the surface on the Earth. Through an integrated Geomonitoring it is possible to observe, among others, the vegetation of the mining areas. The observation of the state of vegetation is an aspect of research using remote sensing methods, e.g. indicators of vegetation. Of course, the reduction of plant vegetation may be caused by other reasons as well. Therefore, an important aspect is to distinguish changes in vegetation resulting affects coming from natural factors (climate changes, long-term droughts or sudden weather phenomena) and the resulting from post-mining processes. This article presents the indicators that have been discovered and used in the research of plant vegetation, which can be used in the post-mining.

1 Introduction

Post-Mining is a very current topic today. This process begins before the end of operation, while the duration is estimated at “eternity” [1-3] Mining can lead to negative consequences that can affect people and the environment and should therefore be managed and countered [3]. Among the important factors that should be observed in the post-mining processes are: Earth movements, geological fault areas (subsurface structure of Earth), surface openings, dumps and sedimentation basins, changes in land use, gas emissions, changes in soil moisture, polder areas, pumping of mine water, infrastructure and surface installations and changes in the health of vegetation [3-13]. Jarocinska and Zagajewski [14] indicate that remote sensing methods make it possible to observe health of vegetation. Geomonitoring of post-mining processes by means of the calculation of vegetation indices, is an important aspect of the present but also future research on post-mining. The study of the processes taking place on the Earth’s surface is an important part of the task of the post-mining management. In current decades, scientific progress has been noticeable in the study of the Earth’s surface using remote sensing methods.
2 The most important are data

Initial data are the beginning of studying every process, so it is always worth subjecting them to evaluation, analysis and interpretation [15]. The assessment of the quality of the preliminary data allows for the identification of the characteristics of the data and the adaptation of the collected materials to a given research project. In terms of data resulting from remote sensing not all data are useful for analysis, some of them have distortions related to a given sensor. Therefore, before data collection is started, criteria should be defined on the basis of which data will be assessed in terms of suitability for a given project. Possible criteria are:

- Spatial extent;
- Time resolution (time space);
- Cloud cover;
- Number and characteristics of spectral ranges (spectral resolution);
- Spatial resolution;
- Scale in the case of maps.

Figure 1 presents the time spaces of individual satellite missions. The first data results from the 1972 Landsat 1 mission [17]. Of course, the first data are less accurate, but it is a “sentimental” source material, because thanks to them it is possible to visualize the surface like it was 50 years ago. It is noticeable that in recent years, it is possible to obtain satellite data from various sources, ranging from:

- NASA space missions: Landsat 7, Landsat 8, MODIS (Moderate Resolution Imaging and Spectroradiometer),
- NASA and Japan’s Ministry of Economy space mission - ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer),
- ESA space missions – Copernicus: Sentinel 1, Sentinel 2, Sentinel 3 and Sentinel 5P.

![Figure 1 Time space of satellite missions. Source: [16-31]](image)

As part of research on the observation of vegetation, one should distinguish space missions that have multispectral scanners. Figure 2 presents the spectral bands of space missions. These devices enable, the calculation indices through the spectral bands. However, not all space missions are equipped with appropriate sensors for research on vegetation indices, so Figure 2 does not show data for Sentinel 1, Sentinel 3 and Sentinel 5P. They are used in other areas: Sentinel 1 - observation of Earth movements, Sentinel 3 –observation of sea and Sentinel 5P – in the study of the composition of the Earth’s atmosphere [27].

The spectral bands or spectral resolution of individual space missions are different from one another. The oldest data – Landsat 1 and Landsat 2 -, present only visible spectral bands. Technological development has led to the development of new instruments that cover new spectral bands. Landsat 3, which was equipped with Multispectral Scanner Instrument (MSS), made it possible to measure thermal ranges. The individual missions: Landsat7, Landsat 8, Sentinel 2, MODIS and ASTER also provide spectral bands in the near-infrared (NIR) and short wavelength infrared (SWIR).
In the field of vegetation research, the visible data (red, green, blue) and near-infrared bands are an important range. Most vegetation indices take into account the above addressed spectral ranges in their formulations.

Another important aspect is the spatial resolution. Spatial or ground resolution means the size of the smallest object that can be distinguished by a sensor, equated to the field pixel of remote sensing image [32]. This is particularly important for the calculation of vegetation indices as not all data have the same resolution. Therefore before proceeding with the study, it is important to refer to Figure 3, which contains the spatial characteristics of the different satellite missions in relation to the frequencies of the spectral bands. The range of individual spatial resolutions is from 10m for Sentinel 2 to 1000m for MODIS. The higher the spatial resolution the more accurate the resulting data will be.

The latest Landsat 7, Landsat 8, Sentinel 2 and ASTER data are characterised by the best fit of the spectral ranges both in terms of spatial resolution and frequency of the spectral ranges for vegetation observations. Therefore, in the literature, research in this area is mostly based on data from Landsat 7, 8 and Sentinel 2 [33]. Understanding the individual spectral bands of the satellites makes it possible to calculate the vegetation indices, which play an important role in the process of Geomonitoring of post-mining processes.
Figure 2 Characteristic of spectral bands of satellite missions. A) Full spectrum of wavelength 0.25 µm-14.5 µm. B) Spectrum of wavelength 0.4 µm - 1.1 µm. Source: [16-31]
Figure 3 Characteristic of spatial resolution of satellite missions. A) Full spectrum of wavelength 0.25μm -14.5μm, B) Spectrum of wavelength 0.4μm - 1.1μm. Source: [16-31]
Observation of the state of vegetation in a given area is one aspect of research work on Geomonitoring of mining areas. The simplest form is the visual assessment of covered and uncovered areas. The results can be represented by the composition of the RGB spectral bands (red, green, blue). It can be used to identify degraded vegetation by long-term drainage [34].

In research on the monitoring of changes in vegetation, the indices of vegetation are used. Buczyńska [33] indicates 4 groups of indicators that can be observed in post-mining processes. These are indicators: “vegetation, determining the water content, geological – enabling the identification of various types of rocks and materials, and intended for the detection of areas that have been damaged by fires”.

The definition of the vegetation index was submitted by Jackson et al. [35]:

“An ideal vegetation index would be highly sensitive to vegetation, insensitive to soil background changes, and only slightly influenced by atmospheric path radiance”

Table 1 presents, in chronological order, a selection of vegetation indices that can be used in the Geo-monitoring of post-mining processes. Table 1 also contains all the abbreviations for the indices used, as well as the formula for their calculation. In the section, different classifications of vegetation indices available in the research literature will be presented.

The first attempt to classify the indices of vegetation was undertaken by Lautenschlager and Perry [36]. They presented the classifications into two categories. The first rearranges the indexes bands 5 and 7 channels (CH5 and CH7 in the Fig.4). They are: AVI [37], NDVI7, PVI7, TVI7 and RVI7. The second, on the other hand, rearranges the indexes using the 4 and 6 channels (CH4 and CH6 in the Fig.4), as well as the indexes containing three or four bands. These are: NDVI6, PVI6, RVI6 and TVI6.

![Figure 4 Idealized reflectance a patterns of herbaceous vegetation and soil from 0.4μm to 1.1μm. Source: [38]](image)

Bariou et al. [39] classified the vegetation indices depending on the combination of the number of spectral bands. The first group is a combination of 2 spectral bands, while second group is a combination 3 or 4 spectral bands.

Huete et al. [40, 41] classified the vegetation indices into two groups: ratio indices – SR [42, 43], RVI [44, 45], NDVI [46] and well as TVI [45], and orthogonal indices – PVI [45] and GVI [47] “The orthogonal indices are distinct from the ratio indices in that isolines of equal ‘greenness’ do not converge at the origin but instead remain parallel to the principal axis of the soil line. The first operate by direct measurement while the second work by indirect measurement. Hence, it can be noted that the

3 Vegetation Indices

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The difference between ratio indices and orthogonal indices is a difference in ‘objective’ between indices” [48, p.114].

Also Baret and Guyot [49] classified the indices into two categories characterized by: slope or by the perpendicular distance in relation to the bare soil line. Mróz and Sobieraj [50] explains that slope basis vegetation indices mean the planks of each point in the NIR-RED space as geometrically equivalent origin point on the viewport. There are: RVI [44, 45], NDVI [46], TVI [38], CTVI [51], TTVI [52]. Vegetation indices based on distance, require of a “soil line” (Eq. 1) and measure the perpendicular distance from each point to that line. There are following indices: PVI [45], DVI [53], SAVI₁ [54], SAVI₂ [55], TSAVI₁ [56], TSAVI₂ [49], MSAVI₁ [57], MSAVI₂ [57], OSAVI [58], WDVI [59].

\[
\text{NIR} = a \times \text{RED} + b \quad (1)
\]

where \(a\) is slope of the bare soil line and \(b\) is intercept of soil line [55].

Determining the slope and intersection of the soil line, requires drawing a line through these clouds of points representing the soil in NIR-RED space (Fig.5).

![Figure 5](image_url)

**Figure 5** Vegetation spectra isolines in NIR-RED wavelength as predicted by ratio-, normalized difference and perpendicular vegetation indices. Source: [54]

The relationship between near infrared and visible reflections from bare soils is generally linear and several vegetation indices have been developed using coefficients for this relationship. The indexes: SAVI₁ [54], SAVI₂ [55], TSAVI₁ [56], TSAVI₂ [49], MSAVI₁ [57], MSAVI₂ [57], OSAVI [58], attempt to study soil samples, assuring that most soil spectra follow the soil line. A significant correction can be found when adaptation to soil is performed [54].
Bannari et al. [48] distinguish two groups of vegetation indices as the first and second generation of indices. The first generation of indices based on empirical methods without taking into account atmospheric effects, soil brightness or soil colour. This series referred to multispectral scanners mounted on Landsat space mission satellites and for clearly defined applications that do not check multipliers for other regions. The second generation of indices, which have significant improvements over the original indexes thanks to mathematical but also physical reasoning – phenomena explaining the interactions between electromagnetic radiation, the atmosphere, vegetation and the soil surface. These include: PVI [40], SAVI$_1$ [54], SAVI$_2$ [55] MSAVI$_1$ [57], MSAVI$_2$ [57], TSAVI$_1$ [49], TSAVI$_2$ [56], ARVI [60], SARVI [53] and NDVI [46]. They are based on the reflectance value corrected for sensor calibrations and atmospheric effects [48].

Among the indices of vegetation one can also distinguish those taking into account the atmospheric influence: ARVI [60], SARVI [60] and VARI [61], and also investigating the content of chlorophyll: CARI [62], MCARI$_1$ [63], MCARI$_2$ [64], MCARI$_3$ [64] and TCI [79].

The classifications presented above show the scientific progress in the field of vegetation indices. In mining areas, the mining activity can affect the vegetation in the area through: indirect environmental stress or direct damage [80]. Vegetation indices, which enable the detection of changes and trends in the vegetation in mining areas, are a particularly important issue for Geomonitoring of post-mining processes. Individual vegetation indicators should also be considered in relation to the data available for the study area and data from satellite missions.

Not all indicators listed in Table 1 are useful for studying post-mining processes. Selected vegetation indices presented in Table 1, which are not sensitive to: biomass change, light soil colour, soil brightness or atmospheric changes, can be useful for vegetation observation in Geomonitoring of post-mining processes, can be divided into 4 groups:

- The first of these should be defined as basic, based on as few spectral channels as possible. These include NDVI [46], AVI [37], EVI$_1$ [65], EVI$_2$ [66], GNDVI [69], TTVI [52], NRVI [49], NDRE [71] and WDRVI [72].
- The second group are the indices based on "soil line". These include: SAVI$_1$ [54], SAVI$_2$ [55], TSAVI$_1$ [56], TSAVI$_2$ [49], MSAVI$_1$ [57], MSAVI$_2$ [57], OSAVI [58] and SARVI [60].
- The third group are indices, which take into account the influence of the atmosphere: ARVI [60], SARVI [60] and VARI [61].
- The fourth group consists of indices that study the chlorophyll content in vegetation: CARI [62], MCARI$_1$ [63], MCARI$_2$ [64], MCARI$_3$ [64] and TCI [79].

The review of world literature provides information on current use of remote sensing data for the analysis of plant cover changes in post-mining areas. The topics of the most frequently undertaken studies concern the monitoring of the reclamation process, including the development of vegetation in degraded areas.

Halounová et al. [81] use the indices: NDVI [46], DVI [53], RVI [43], PVI [57], SAVI$_1$ [54], MSAVI$_1$ [57], TSAVI$_1$ [49], TSAVI$_2$ [56], EVI$_1$ [65] and WDVI [59] to assess the success of reclamation of deteriorated areas in Northern Bohemia. Also Matejicek and Kopackova [82] conducted analyses of land cover changes in the north-western Czech Republic in the period 1985-2009 using calculated satellite NDVI [46] on the basis of Landsat satellite images.

Koruyan et al. [83] conducted analyses of vegetation changes in the Mugla area (Turkey) in the period 2001-2009 using NDVI [46] calculated from Aster, Landsat 5 and Landsat 7 satellite data. Erener [84] conducted a study on vegetation in the Seyitömer open pit coal mine area (Turkey) using SR [42,43], RSR (Reduced Simple Ratio) [85] and NDVI [46], based on Landsat 1987-2006 satellite images.

Also Raval et al. [86] carried out an attempt to estimate biomass production in a reclaimed coal mining area of Wise County (USA) on the basis of Landsat 5 satellite images for the period 2008-2010. The authors used the following indices in their study: NDVI [46], NDMI (Normalized Difference Moisture Index) [87], SVR (shortwave-infrared/visible ratio) [88] and MSR [68].
Ma et al [80] conducted a study on monitoring changes in the Changhe River area (China) based on calculated vegetation indices: SR [43], NDVI [46], SAVI [54], TSAVI [49], PVI [40], NLI [89], MSR [68] and TC greenness [90], derived from Landsat space missions over the period 2001-2013. Padmanaban et al. [91] conducted a study on vegetation changes based on the NDVI [46] index calculated from Landsat data 2013-2016. The authors indicated the location of two subsidence zones in the Kircheller Heide area (Germany), these phenomena were a consequence of rising groundwater table.

Also Buczyńska and Blachowski [92] in their study on the analysis of changes in vegetation in the area of the closed Babina mine (Poland) using Landsat satellite images in the period 1989-2019. The authors used the indicators in their publication: NDVI [46], GNDVI [69] and EVI [65].

The above case studies, which use individual vegetation indicators in the calculations, indicate the legitimacy of using vegetation indicators in Geomonitoring of post-mining processes. The article presents a documented structural procedure and a summary, which aims to indicate which vegetation indications are justified in the observation of post-mining processes.
Table 1. Chronological table of selected vegetation indices found in the literature from 1968 to 2020

| Index               | Abbreviation | Formula                                      | Description                                                                 | References |
|---------------------|--------------|----------------------------------------------|----------------------------------------------------------------------------|------------|
| Simple Ratio        | SR           | \(\frac{p_{\text{NIR}}}{p_{\text{RED}}}\) | + simple formula for calculations - value about 1 = soil, differentiating stressed vegetation from unstressed areas<br> + enhance the contrast between the ground and vegetation<br> - sensitive to ground optical properties<br> - not an ideal measure of vegetation biomass, which may be susceptible to external factors (the way of lighting and tilting the photo, the influence of atmospheric factors) | 42, 43, 49, 73 |
|                     |              | \(\frac{A}{B}\)                              |                                                                            |            |
| Ratio Vegetation Index | RVI          | \(\frac{\frac{p_{\text{NIR}}}{p_{\text{RED}}}}{\frac{p_{\text{NIR}}}{p_{\text{RED}}}}\) | + simple formula for calculations<br> + tool to estimate and monitor green biomass,<br> + enhance the contrast between the ground and vegetation<br> - sensitive to ground optical properties<br> - very sensitive to biomass and shows good correlation with plant biomass<br> - not an ideal measure of vegetation biomass, which may be susceptible to external factors (the way of lighting and tilting the photo, the influence of atmospheric factors) | 44, 45, 49, 73, 74 |
| Normalized Difference Vegetation Index | NDVI        | \(\frac{p_{\text{NIR}} - p_{\text{RED}}}{p_{\text{NIR}} + p_{\text{RED}}}\) | + simple formula for calculations<br> + sensitive reaction to green vegetation<br> + related to canopy photosynthesis<br> - not an ideal measure of vegetation biomass, which may be susceptible to external factors (the way of lighting and tilting the photo, the influence of atmospheric factors)<br> - sensitive to light, soil color | 46, 73, 76 |
| Transformed Vegetation Index | TVI | \(\sqrt{\frac{\frac{p_{\text{NIR}}}{p_{\text{RED}}}}{\frac{p_{\text{NIR}}}{p_{\text{RED}}}}} + 0.5\) | the added value (0.5) to all values and taking the square root of NDVI was intended to eliminate negative values. | 38, 45 |
| Green Vegetation Index | GVI | \(-0.290 * \text{MSS}4 + 0.562 * \text{MSS}5 + 0.491 * \text{MSS}7\) | minimizes the effects of background soil while emphasizing green vegetation. Values range from -1 to 1. | 47, 48, 75 |
| Difference Vegetation Index | DVI | \(\frac{\text{MSS}5}{\text{MSS}7 - \text{MSS}5}\) Where: \(\gamma = 2 - 4\), the slope of the soil line, \(\text{MSS}7 = \text{near-infrared band}, \text{MSS}5 = \text{red band}\) | + simple formula for calculations<br> DVI weigh up the near-infrared band by the slope of the soil line | 45 |
| Ashburn Vegetation Index | AVI | \(\frac{\gamma}{\text{NIR}} - \rho_{\text{RED}}\) | + simple formula for calculations<br> AVI is presented as an indicator of growing green vegetation. | 37, 48, 51 |
| Corrected Transformed Vegetation Index | CTVI | \(\frac{N_{\text{DVI}} + 0.5}{\sqrt{\text{ABS}(N_{\text{DVI}} + 0.5)}}\) | adding a constant of 0.5 does not eliminate all negative values. The proposed formula by Perry and Lautenschlager [51] suppresses the negative values in NDVI and TVI. | 51, 48 |
| Perpendicular Vegetation Index | $PV_{1}$ | $\sqrt{(R_{GG} - R_{P}) ^2 + (R_{GG} - R_{P}) ^2}$ | Enables the definition of vegetation and non-vegetation for dry and semi-dry areas. Sensitive to atmospheric changes, requires atmospheric data correction. |
|-------------------------------|----------|-------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|
|                               | $PV_{2}$ | $\frac{\sqrt{a} R_{NIR} - \sqrt{b} R_{RED} + b}{\sqrt{a} + 1}$ | Uses soil line It makes it possible to distinguish water from vegetation, which was not possible with $PV_{1}$ |
|                               | $PV_{3}$ | $\frac{1}{\sqrt{a} + 1} (R_{NIR} - a \cdot R_{RED} - b)$ | Uses soil line Less influenced by soil brightness as opposed to ratio indices. |
|                               | $PV_{4}$ | $\frac{1}{\sqrt{a} + 1} (WDVI - b)$ | Uses soil line Formula WDVI substituted PW3 equation. |
|                               | $PV_{5}$ | $\frac{1}{\sqrt{a} + 1} (\frac{R_{NIR}}{R_{RED}} - 1)$ | Uses soil line Avoids the negative results |
| Difference Vegetation Index   | $DVI$    | $\rho_{NIR} - \rho_{RED}$ | Uses difference between near-infrared and red bands to highlight healthy vegetation. |
|                               | $SVVI_{1}$ | $\frac{(\rho_{NIR} - \rho_{RED})(1 + L)}{(\rho_{NIR} + \rho_{RED})(1 + L)}$ | This transformation is most appropriate for identifying soil induced changes in vegetation indices. Minimalize soil-brightness in fluxes with constant $L$. |
|                               | $SVVI_{2}$ | $\frac{\rho_{NIR}}{\rho_{RED} + 1}$ | Uses soil line Minimalize soil-brightness in fluxes. |
| Transformed Soil Adjusted Vegetation Index | $TSAVI_{1}$ | $\frac{a (\rho_{NIR} - \rho_{RED}) + b (\rho_{RED} + \rho_{NIR}) - a b}{(\rho_{RED} + a + (\rho_{NIR} + b - a b)^2}$ | Uses soil line This index assumes that the soil line has arbitrary slope and intercept, and it uses one of these values to adjust the vegetation index. |
|                               | $TSAVI_{2}$ | $\frac{a (\rho_{NIR} + \rho_{RED}) + b (\rho_{RED} - \rho_{NIR}) + 0.08 (1 + a b)}{(\rho_{RED} + a + (\rho_{NIR} + b - a b)^2} + 0.08(1 + a b)}$ | $TSAVI_{2}$ is modified version of $TSAVI_{1}$ that has been adjusted with correction factor of 0.08 which minimizes the effect of soil brightness calculated from this formula is equal to 0 in the case of bare soils and approaches 0.70 for very dense forest cover. |
| Weighted Difference Vegetation Index | $WDVI$ | $\rho_{NIR} - \rho_{RED}$ | very sensitive to atmospheric variations |
| Normalized Ratio Vegetation Index | $NRVI$ | $\frac{SVI - 1}{SVI + 1}$ | estimation of vegetation with lower vegetation densities |
| Vegetation Index | Formula | Description |
|------------------|---------|-------------|
| ARVI             | \( \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}} \times (1 + L) \) | Used to eliminate atmospheric effects. Used for regions with a high aerosol content (rain, fog, dust, smoke, air pollution). |
| SARVI            | \( \frac{(1 + L)(\rho_{\text{NIR}} - \rho_{\text{RED}})}{(\rho_{\text{NIR}} + \rho_{\text{RED}} + L)} \) | Corrects both soil and atmospheric effects by adding a constant L to the ARVI formula. |
| CARI             | \((\rho_{700\text{nm}} - \rho_{865\text{nm}})/(2(\rho_{700\text{nm}} + \rho_{865\text{nm}})))\) | Minimizes effects of nonphotosynthetic materials on spectral estimates of absorbed photosynthetically active radiation. |
| MSAVI1           | \( \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}} + 1} \) | Minimizes the soil-brightness effect with constant L. |
| EVI              | \( \frac{2 \rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}} + \frac{1}{2}(\rho_{\text{NIR}} + \rho_{\text{RED}} - 2 \rho_{\text{RED}}}) \) | EVI1 corrects the effects of atmospheric factors and soil signals simultaneously in areas with dense canopies. |
| EVI2             | \( \frac{2 \rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}} + \frac{1}{3}(\rho_{\text{NIR}} + \rho_{\text{RED}} - 1)} \) | EVI2 is designed to be used by sensors that do not acquire the blue channel but calibrated to achieve similar values to EVI1. |
| RDVI             | \( \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}} \) | The RDVI is similar in application to the SAVI. It suppresses results from bare ground and sun. In contrast to the SAVI, its informative value is not very good in sparsely overgrown or dry areas. |
| MSR              | \( \frac{\rho_{\text{NIR}}}{\rho_{\text{RED}}} + 1 \) | This index was developed as an improvement over RDVI by combining the Simple Ratio into the formula. The result is increased sensitivity to vegetation biophysical parameters. |
| GNDVI            | \( \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}} \) | It is most often used in assessing the moisture content and nitrogen concentration in plant leaves. It is more sensitive to chlorophyll concentration. It is used in assessing depressed and aged vegetation. |
| OSAVI            | \( \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}} + L} \) | The difference between SAVI and OSAVI is the constant value of L, which is 0.16. The OSAVI allows a greater variation in soil values and is more sensitive to vegetation. |
| TTVI             | \( \sqrt{\rho_{\text{RED}}(\text{GNDVI} + 0.9)} \) | Reduces image noise due to an overestimation of the greenness. |
**Vegetation Index**

| Triangular Vegetation Index | TVI | $0.5^*(120(\mu_{\text{NIR}} - \mu_{\text{GREEN}}) + (\mu_{\text{RED}} - \mu_{\text{GREEN}}))$ | Sensitive to both chlorophyll content. |
|-----------------------------|-----|-------------------------------------------------|--------------------------------------|

*Vegetation Index* is sensitive to both chlorophyll content.

**Triangular Vegetation Index (TVI)**

$TVI = 0.5^*(120(\mu_{\text{NIR}} - \mu_{\text{GREEN}}) + (\mu_{\text{RED}} - \mu_{\text{GREEN}}))$

Where: $\mu_{\text{NIR}} = 750\text{nm}$, $\mu_{\text{GREEN}} = 550\text{nm}$ and $\mu_{\text{RED}} = 670\text{nm}$

**Normalized Difference Red Edge Index**

$\text{NDRE} = \frac{\mu_{\text{NIR}} - \mu_{\text{RED edge}}}{\mu_{\text{NIR}} + \mu_{\text{RED edge}}}$

The red-edge band is very sensitive to medium to high levels of chlorophyll content. Hence, red-edge is a good indicator of crop health in the mid to late stage crops where the chlorophyll concentration is relatively higher.

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The red-edge band is very sensitive to medium to high levels of chlorophyll content. Hence, red-edge is a good indicator of crop health in the mid to late stage crops where the chlorophyll concentration is relatively higher.

**Triangular Vegetation Index (TVI)**

$TVI = 0.5^*(120(\mu_{\text{NIR}} - \mu_{\text{GREEN}}) + (\mu_{\text{RED}} - \mu_{\text{GREEN}}))$

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4 Conclusions
Post-mining processes on the Earth's surface have a negative impact on the surrounding environment. Geomonitoring of post-mining processes on the Earth's surface is a very topical issue. The observation of the state of vegetation using remote sensing methods is one of the aspects of Geomonitoring in post-mining. Remote sensing methods allow the development of research problems for large areas, which is an undoubted advantage of this method. Before starting the research, it is necessary to get acquainted with the characteristics of the initial data, especially with: spatial and spectral resolution. The best data characteristics are possessed by space missions: Landsat 7, Landsat 8 and Sentinel 2, both in terms of spatial resolution and spectral ranges, which are used to calculate vegetation indices. These data are publicly available. One limitation that may occur is cloud cover. The higher the spatial resolution of the satellite data, the more accurate the data obtained will be. This study presents a chronological review of vegetation indices, which can be used in the post-mining. The proposed group of vegetation indices: basic, soil line based, atmospheric and chlorophyll content based, form the basis for further research in post-mining.

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