

Saline Soils Areas Variability Evaluation through Remote Sensing Techniques - Case Study Socodor ATU, Romania

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Abstract. The study used remote sensing techniques to analyze the variability of an area affected by salinity soils. The study area was within the Socodor ATU, Arad County, Romania. Satellite scenes were acquired in the Sentinel 2 system, in the summer season, June and July, between 2020 and 2024. The Brightness Index (BI), Salinity Index (SI), Salinity Index 2 (SI2) and Normalized Salinity Index (NDSI) were calculated based on the spectral data. A very strong positive correlation was recorded between SI2 and BI throughout the study period ($p < 0.001$). At the level of the other indices, the correlation presented variable levels of intensity. Differences were recorded between the values of the indices during the study period. High values of the SI, SI2 and BI indices were recorded in 2022, compared to 2020 and 2024 ($p < 0.001$). In the case of the NDSI index, higher values were recorded in 2020 ($p < 0.001$). The variation of the BI index in relation to SI2 was described by a polynomial mathematical model, with a very strong positive correlation, $p = 0$. In relation to the principal components, there was a differentiated positioning of the indices in the case of 2020 compared to 2022 and 2024, and a high degree of similarity regarding the positioning of the indices in 2022 and 2024. In 2020, the NDSI, BI and SI2 indices were positioned in PC1, with very strong positive action, and the SI index was positioned independently. In the case of the years 2022 and 2024, the BI and SI2 indices were positioned in PC1 with very strong positive action, and the SI and NDSI indices were positioned in PC2, with very strong positive action (the SI index), and strong negative action for the NDSI index (2022), respectively moderate negative action for the NDSI (2024).

Keywords: multivariate analysis, NDSI, remote sensing, saline soils, salinity index, variability

INTRODUCTION

Soil salinization and salinity represent a major environmental problem, which, associated with climate change, determined an increase in socio-economic impact on a global scale (Hassani et al., 2021; Haj-Amor et al., 2022; Singh, 2022). The salinization is a complex process, attributed to natural and anthropogenic factors, and salinized areas are primarily associated with arid climatic zone (Stavi et al., 2021; Zhang et al., 2022; Liu et al., 2023).

Salinized soils have been studied in relation to different topoclimates (arid, semi-arid areas) but also in relation to climate changes that amplify the salinization process (Chaieb et al., 2019; Bannari and Al-Ali, 2020; Corwin, 2021). Causes and influencing factors of the salinization process were analyzed and characterized in various conditions of soils affected by salinity, in relation to the intensity of the process and the physical, chemical, biological and microbiological conditions in the soil (Li et al., 2022; Li et al., 2023; Shokri et al., 2024).

The salinization phenomenon presents spatial and temporal dynamics and has been analyzed in relation to influencing factors for different categories of natural and agricultural ecosystems (Hu et al., 2023; Lekka et al., 2023; Zhao et al., 2023). Models for predicting the dynamics of soil salinization have been generated in studies from local to global scales, due to the importance of this process and the ecological and economic effects it generates (Allbed et al., 2014; Hassani et al., 2020; Thangarasu et al., 2025).

The recovery of areas with saline soils is a challenge, and numerous studies have analyzed methods and techniques for soil improvement, and methods for the recovery of lands affected by salinization (Elmeknassi et al., 2024; Hirich and Bhargava, 2024; Zhou et al., 2024). The restoration of areas affected by salinity has been the subject of numerous studies and research to limit the extension of the salinization process, to recover areas affected by salinity for productive purposes (Lee et al., 2024; Daba, 2025).

Soil biodiversity, flora and fauna biodiversity have been studied and evaluated in dynamics in relation to soil salinity, and areas affected by salinity (Jiang et al., 2022; Jia et al., 2023).

Considering the environmental and socio-economic impact it presents, saline areas are monitored through ground studies and techniques based on remote sensing and imaging analysis (Stavi et al., 2021; Sarkar et al., 2023; Mirzaee et al., 2024; Salem and Jia, 2024; Hossain et al., 2025). The technique based on remote sensing uses information in the form of satellite scenes, spectral data and a series of specific indices that express soil salinity, and properties of the vegetation covering the areas affected by salinity (Wang et al., 2022; Bandak et al., 2024; Saad et al., 2024; Salem and Jia, 2024).

The present study analyzed the spatial and temporal dynamics of a salinized area through remote sensing

and explained the positioning of the specific indices calculated in relation to the main components.

MATERIAL AND METHODS

The studied area is located in western Romania, within the Socodor ATU perimeter, Arad County. On the Socodor ATU area, there is the Socodor Saline Soils Natural Reserve, figure 1. The study analyzed the variability of the salinized area based on satellite images (Sentinel 2), period 2020 – 2024.

From a climatic point of view, the studied area falls under the temperate continental-moderate climate type, with slight Mediterranean influences. The multiannual average temperature is 10.6 °C at Chisinau Cris locality. The warmest month is July, with an average temperature of 21.4 °C, and the coldest month is January with an average temperature of 1.4 °C. The territory of the Socodor commune, includes extensive areas of good and very good quality soils, favorable for agricultural crops. Within the Socodor Saline Soils Natural Reserve, with an area of approx. 95 ha, saline soils and specific vegetation predominate.

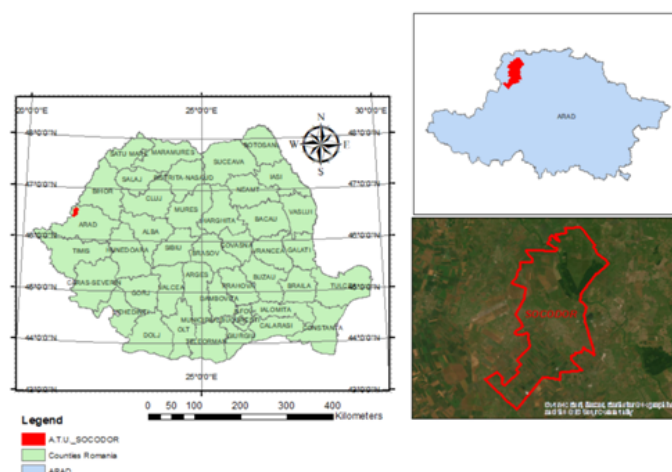


Figure 1. Study location, Socodor ATU, Arad County, Romania

This scientific research used the Copernicus remote sensing platform to acquire satellite images from the Sentinel 2 system (8). The Sentinel 2 system is composed of 13 spectral bands with spatial resolutions of 10, 20 or 60 meters.

The satellite scenes were taken during the summer season, on the following dates: 10.07.2020, 20.06.2022, 09.07.2024. The source images (Sentinel 2) were analyzed to obtain spectral values. Based on the spectral data (spectral bands), a series of indices specific to the lands affected by salts were calculated, table 1 (ESRI, 2025).

Table 1. Indices used to characterize the salinity of the studied area

Index	Equation	Eq. no	Authors
Brightness Index	$BI = \sqrt{Red^2 + NearInfraRed^2}$	(1)	Khan et al. (2001)
Salinity Index	$SI = \sqrt{Green \times Red}$	(2)	Douaoui et al. (2006)
Salinity Index 2	$SI2 = \sqrt{Green^2 + Red^2 + NearInfraRed^2}$	(3)	Douaoui et al. (2006)
Normalized Salinity Index	$NDSI = \frac{Red - NearInfraRed}{Red + NearInfraRed}$	(4)	Odeh and Onus (2008)

The values recorded for the calculated indices were analyzed by descriptive statistical analysis for the general characterization of the results. Correlation analysis was applied to find out the interdependence between the indices. Regression analysis was applied to describe the interdependence relationship between certain representative indices. The spatial dynamics of the studied area was represented based on the indices, in map format (ESRI, 2025). Multivariate analysis was applied to find out the positioning of the indices over the study period in relation to the principal components. In relation to the purpose of the study, the PAST software (Hammer et al., 2001), and JASP software (2022) were used.

RESULTS AND DISCUSSIONS

Satellite images were taken during the years 2020, 2022, and 2024, and based on the spectral data, specific indices for the characterization of salinized areas, SI, SI2, BI, and NDSI, were calculated. Descriptive statistical analysis on a number of 9458 values related to each index, led to the results in Table 2.

Based on the data series, obtained from the calculation for each index, maps were generated that expressed the dynamic variation of the indices during the study period, in the area with salinized soils in the Socodor protected area, Arad County, Romania, figure 2.

Table 2. Descriptive statistics for index values for the Socodor area, Arad County, Romania

Statistical Parameters	SI_2020	SI2_2020	BI_2020	NDSI_2020	SI_2022	SI2_2022	BI_2022	NDSI_2022	SI_2024	SI2_2024	BI_2024	NDSI_2024
N	9458	9458	9458	9458	9458	9458	9458	9458	9458	9458	9458	9458
Min	1330.36	3985.83	3702.47	0.18	1706.45	4328.05	3867.40	0.11	1694.38	4373.68	3996.42	0.15
Max	3163.21	6801.27	6564.48	0.65	3378.47	7129.75	6531.42	0.46	2999.66	6424.73	6011.62	0.55
Mean	1891.82	5111.79	4729.49	0.39	2385.77	5423.54	4926.95	0.25	2095.47	5145.25	4711.48	0.33
Std. error	1.85	4.86	5.20	0.00	1.59	3.25	3.25	0.00	1.24	3.06	3.18	0.00
Stand. dev	179.78	472.82	505.59	0.10	154.82	315.60	316.12	0.06	120.84	298.07	309.02	0.06
Median	1880.51	5030.60	4634.01	0.38	2367.42	5387.39	4888.61	0.24	2082.65	5085.66	4644.10	0.31
25 prentil	1757.84	4729.79	4316.39	0.31	2287.31	5185.47	4689.34	0.22	2019.76	4937.34	4499.50	0.29
75 prentil	1992.91	5444.55	5084.37	0.47	2463.07	5610.21	5106.98	0.28	2149.67	5297.83	4860.31	0.35
Skewness	0.89	0.59	0.66	0.36	1.16	0.61	0.69	0.99	1.34	0.95	1.09	1.11
Kurtosis	2.33	-0.35	-0.31	-0.95	3.45	0.50	0.47	0.89	4.57	0.83	1.22	1.30
Geom. mean	1883.61	5090.54	4703.43	0.38	2380.95	5414.53	4917.05	0.25	2092.13	5136.89	4701.76	0.32
Coeff. var	9.50	9.25	10.69	25.13	6.49	5.82	6.42	21.87	5.77	5.79	6.56	17.03

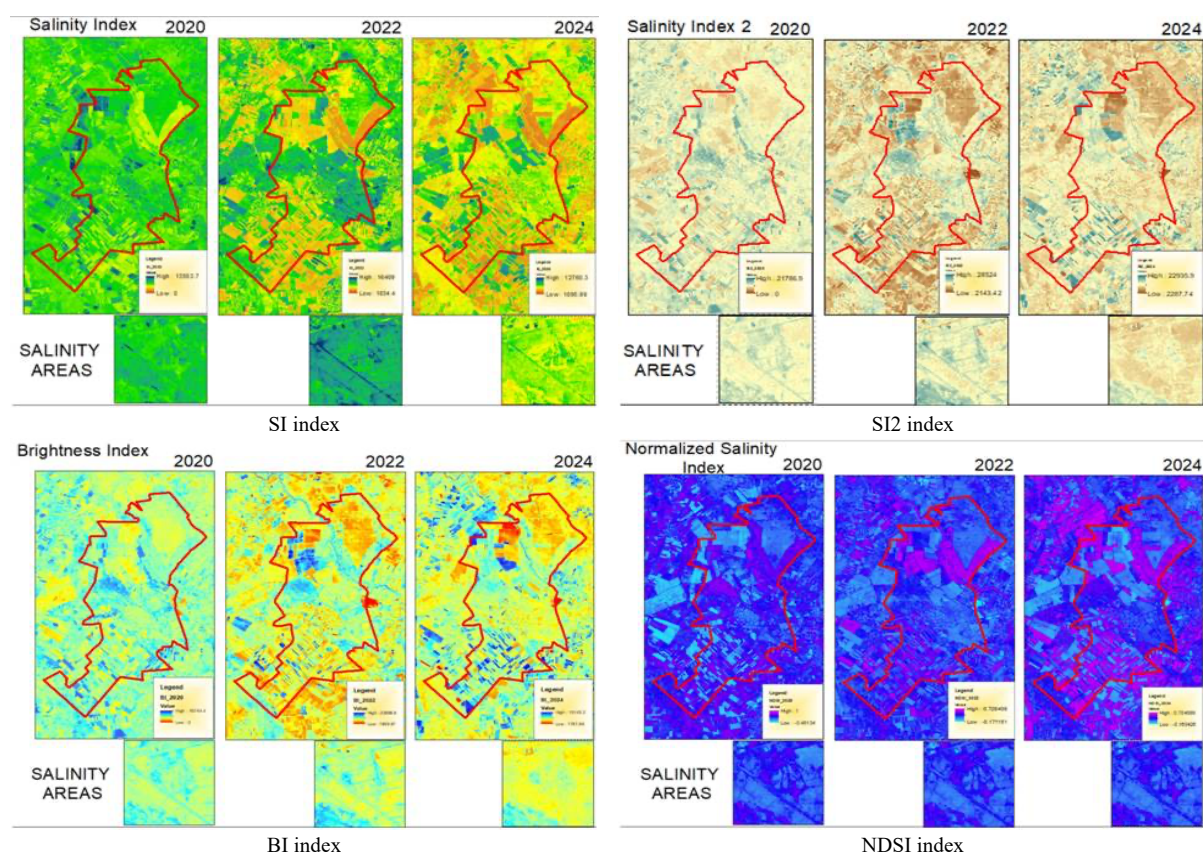


Figure 2. Indices in map format representation, Socodor, Arad County, Romania, 2020 – 2024 period

From the analysis of the coefficient of variation (CV) values, table 2, moderate variability was found for the NDSI index in 2020 (CV = 25.13) and in 2022 (CV = 21.87) and low variability for the other indices, throughout the study period.

The correlation analysis showed the interdependence between the indices in conditions of statistical safety ($p < 0.001$), table 3. In 2020, a very strong positive correlation was recorded between SI2 and BI ($r = 0.995$), strong negative correlation between SI and NDSI ($r = -0.802$), and strong positive correlation between BI and NDSI ($r = 0.843$). A moderate correlation was recorded between SI2 and NDSI ($r = 0.745$). Weak correlation was recorded in the conditions of 2020 between the other indices.

In 2022, very strong correlation was recorded between SI2 and BI ($r = 0.988$), and weak correlation between SI and NDSI ($r = -0.617$) and between BI and NDSI ($r = 0.588$). Low values of the correlation coefficient were recorded between the other indices.

In 2024, very strong positive correlation was recorded between SI2 and BI ($r = 0.992$), moderate correlation between BI and NDSI ($r = 0.738$). Weak correlation was recorded between SI and NDSI ($r = -0.670$) and between SI2 and NDSI ($r = 0.652$). Among the other indices, at the level of 2024, low values of the correlation coefficient were recorded.

Similar levels of correlation were observed during the study period for the SI2 indices with BI, at very strong positive correlation level. Differentiation of the level of correlation was observed for the SI, SI2 and BI indices with the NDSI index, which was at strong and moderate correlation level in 2020, and at a lower level in 2022 and 2024.

Table 3. The level of correlation between indices during the study period

Statistical parameters	Variable	SI_2020	SI2_2020	BI_2020	NDSI_2020	Variable	SI_2022	SI2_2022	BI_2022	NDSI_2022	Variable	SI_2022	SI2_2022	BI_2022	NDSI_2022
Pearson's r	SI_2020	—				SI_2022	—				SI_2024	—			
p-value	SI_2020	—				SI_2022	—				SI_2024	—			
Pearson's r	SI2_2020	-0.278***	—			SI2_2022	0.405***	—			SI2_2024	0.117***	—		
p-value	SI2_2020	< .001	—			SI2_2022	< .001	—			SI2_2024	< .001	—		
Pearson's r	BI_2020	-0.375***	0.995***	—		BI_2022	0.262***	0.988***	—		BI_2024	-0.004	0.992***	—	
p-value	BI_2020	< .001	< .001	—		BI_2022	< .001	< .001	—		BI_2024	0.677	< .001	—	
Pearson's r	NDSI_2020	-0.802***	0.785***	0.843***	—	NDSI_2022	-0.617***	0.464***	0.588***	—	NDSI_2024	-0.670***	0.652***	0.738***	—
p-value	NDSI_2020	< .001	< .001	< .001	—	NDSI_2022	< .001	< .001	< .001	—	NDSI_2024	< .001	< .001	< .001	—

Note: *** represents significance for $p < 0.001$

The relationship between the BI index values and the SI2 index values in the study years was described by equation (5) for the year 2020, with $R^2 = 0.989$, $p = 0$, by equation (6) for the year 2022, with $R^2 = 0.975$, $p = 0$, and respectively by equation (7) for the year 2024, with $R^2 = 0.986$, $p = 0$. The graphical distributions of equations (5), (6), and (7), and the related BI and SI2 index values, are presented in figure 3. The interdependence of BI values in relation to SI2 values was at a very strong level, according to the regression coefficient values registered.

$$BI = 3.742 \text{ E} - 05x^2 + 0.6705x + 315.6 \quad (5)$$

where: BI - Brightness Index; x - Salinity Index 2 (SI2) pentru anul 2020

$$BI = 1.74 \text{ E} - 05x^2 + 0.7972x + 89.68 \quad (6)$$

where: BI - Brightness Index; x - Salinity Index 2 (SI2) pentru anul 2022

$$BI = 7.656 \text{ E} - 05x^2 + 0.2194x + 1549 \quad (7)$$

where: BI - Brightness Index; x - Salinity Index 2 (SI2) pentru anul 2024

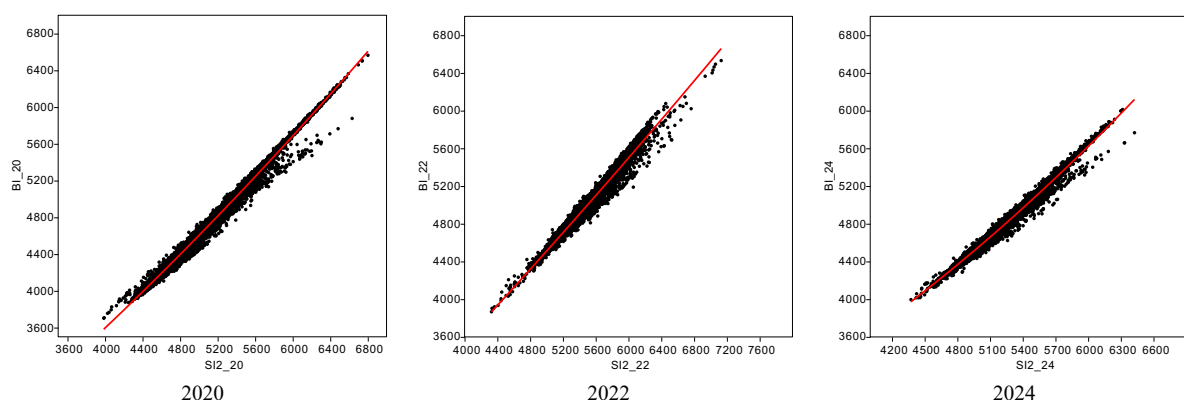


Figure 3. Distribution of BI values in relation to SI2 during the study period

For each index, a comparative analysis was made between the values recorded during the study period. The analysis of the indices values in 2022 compared to 2020 led to the results in table 3. In the case of the SI, SI2 and BI indices, the mean values in 2022 presented positive differences compared to the mean values in 2020, at a statistical safety level of $p < 0.001$ (***) . In the case of the NDSI index, the mean value in 2022 presented a negative difference compared to the mean value in 2020, at a statistical safety level ($p < 0.001$, ^{ooo}).

Table 3. Differences between the indices in 2022 compared to 2020

Statistical Parameters	SI	SI2	BI	NDSI
Given mean: 2022	2385.77	5423.54	4926.95	0.25
Sample mean: 2020	1891.80	5111.80	4729.50	0.39
95% conf. interval:	(1888.2 1895.4)	(5102.3 5121.3)	(4719.3 4739.7)	(0.39149 0.39548)
Difference:	493.95	311.75	197.46	-0.14
95% conf. interval:	(490.33 497.57)	(302.22 321.28)	(187.27 207.65)	(0.14149 0.14548)
t :	-267.20	-64.12	-37.98	141.12
p (same mean):	0	0	<0.001	0
Means are significantly different	***	***	***	ooo

The analysis of the indices values in 2024 compared to 2020 led to the results in table 4. In the case of the SI and SI2 indices, the mean values in 2024 showed positive differences compared to the mean values in 2020, at the level of statistical safety ($p < 0.001$, ***). In the case of the BI and NDSI indices, the mean values in 2024 showed a negative difference compared to the mean values in 2020, under conditions of statistical safety ($p < 0.001$, ^{ooo}).

Table 4. Differences between the indices in 2024 compared to 2020

Statistical Parameters	SI	SI2	BI	NDSI
Given mean: 2024	2095.47	5145.25	4711.48	0.33
Sample mean: 2020	1891.80	5111.80	4729.50	0.39
95% conf. interval:	(1888.2 1895.4)	(5102.3 5121.3)	(4719.3 4739.7)	(0.39149 0.39548)
Difference:	203.65	33.46	-18.01	-0.06
95% conf. interval:	(200.03 207.27)	(23.932 42.992)	(7.8153 28.197)	(0.06149 0.065476)
t :	-110.16	-6.88	3.46	62.44
p (same mean):	0	<0.001	<0.001	0
Means are significantly different	***	***	ooo	ooo

The analysis of the indices values in 2024 compared to 2022 led to the results in table 5. In the case of the SI, SI2 and BI indices, the mean values in 2024 presented negative differences compared to the mean values in 2022, at the level of statistical safety ($p < 0.001$, ^{ooo}). In the case of the NDSI index, the mean value in 2024 presented a positive difference compared to the mean value in 2022, under statistical safety ($p < 0.001$, ***).

Table 5. Differences between the indices in 2024 compared to 2022

	SI	SI2	BI	NDSI
Given mean: 2024	2095.47	5145.25	4711.48	0.33
Sample mean: 2022	2385.80	5423.50	4926.90	0.25
95% conf. interval:	(2382.7 2388.9)	(5417.2 5429.9)	(4920.6 4933.3)	(0.25159 0.25382)
Difference:	-290.30	-278.29	-215.47	0.08
95% conf. interval:	(287.18 293.42)	(271.93 284.65)	(209.1 221.84)	(0.076183 0.078412)
t :	182.35	85.75	66.29	-136.00
p (same mean):	0	0	<0.001	0
Means are significantly different	ooo	ooo	ooo	***

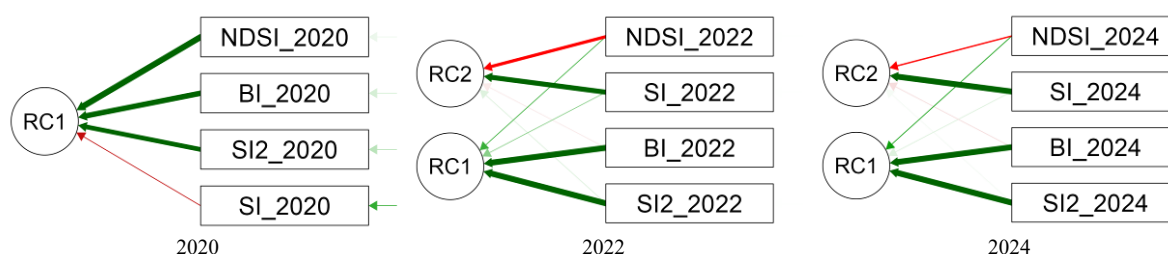
The multivariate analysis showed the classification of the indices, by study years, into the principal components. For the year 2020, the NDSI, BI and SI2 indices were positioned in PC1, and the SI index presented an independent position, table 6, figure 4. The indices included in PC1 showed a very strong positive action, with $r = 0.974$ (NDSI_2020), $r = 0.942$ (BI_2020), and $r = 0.903$ (SI2_2020), respectively.

For the year 2022, the BI and SI2 indices were positioned in PC1, and the SI and NDSI indices were positioned in PC2, table 6, figure 4. The indices positioned in PC1 showed very strong positive action, with $r = 0.997$ (BI_2022), respectively $r = 0.996$ (SI2_2022). In PC2, the SI_2022 index showed very strong positive action, with $r = 0.946$, and the NDSI_2022 index showed strong negative action, with $r = -0.838$.

For the year 2024, the SI2 and BI indices were positioned in PC1, and the SI and NDSI indices were positioned in PC2, table 6, figure 4. The indices positioned in PC1 showed very strong positive action, with $r = 0.999$ (SI2_2024), respectively $r = 0.995$ (BI_2024). In PC2, the SI_2024 index showed very strong positive action ($r = 0.995$), and the NDSI_2024 index showed moderate negative action ($r = -0.737$).

Table 6. Component loadings

Component	PC1	PC2	Uniqueness
NDSI_2020	0.974		0.052
BI_2020	0.942		0.113
SI2_2020	0.903		0.185
SI_2020			0.561
BI_2022	0.997		0.002
SI2_2022	0.996		0
SI_2022		0.946	0.002
NDSI_2022		-0.838	0.003
SI2_2024	0.999		0
BI_2024	0.995		0.001
SI_2024		0.995	0.002
NDSI_2024		-0.737	0.003

**Figure 4.** Path Diagram for the indices analyzed during the study period

A differentiation in the positioning of the indices in relation to the main components was observed in the case of 2020 compared to 2022 and 2024, respectively a high degree of similarity regarding the positioning of the indices in 2022 and 2024. In the case of 2022 and 2024, the BI and SI2 indices were positioned in PC1 with

very strong positive action, and the SI and NDSI indices were positioned in PC2, with very strong positive action for the SI index, and strong negative action for the NDSI index (2022), respectively moderate negative action for the NDSI (2024).

The characteristics of the components are presented in Table 7, with the graphical distribution of the Eigenvalue – Component relationship in Figure 5.

Table 7. Component characteristics

Year	Component	Unrotated solution			Rotated solution		
		Eigenvalue	Proportion var.	Cumulative	SumSq. Loadings	Proportion var.	Cumulative
2020	Component 1	3.089	0.772	0.772	3.089	0.772	0.772
2022	Component 1	2.401	0.6	0.6	2.383	0.596	0.596
	Component 2	1.591	0.398	0.998	1.609	0.402	0.998
2024	Component 1	2.652	0.663	0.663	2.451	0.613	0.613
	Component 2	1.342	0.335	0.998	1.543	0.386	0.998

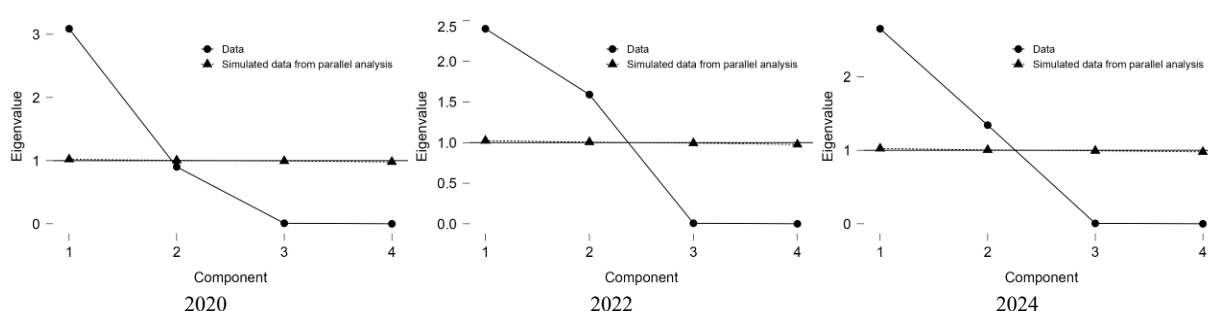


Figure 5. Scree plots for the Eigenvalue - Component relationship for the indices analyzed during the study period (2020 – 2024)

Remote sensing-based techniques have high applicability in studies of terrestrial areas for the general evaluation of natural or anthropogenic areas, for classification into different categories of use, description of spatial and temporal variability in the studied areas (Buchanan et al., 2015; Herbei and Sala, 2015, 2020; Mao et al., 2020). Remote sensing ensured the inventory and monitoring of areas affected by salinity, and the evaluation of the spatial and temporal variability of the areas considered in the study (Sarkar et al., 2023; Mirzaee et al., 2024; Hossain et al., 2025).

Specific indices for characterizing areas affected by salinity have been used in remote sensing-based studies to describe the intensity of soil salinization, to evaluate the dynamics of surfaces affected by salinity, as well as trends in soil recovery through specific improvement methods (Wang et al., 2022; Salem and Jia, 2024).

The remote sensing technique, with images in the Sentinel 2 system, provided in the present study information in the form of images, spectral data, and specific calculated indices, which expressed with statistical safety the state of the Socodor area, with soils affected by salinity. The comparative analysis of the indices calculated during the study period showed statistically significant differences at the $p < 0.001$ level. This expressed the spatial and temporal variability of the studied area, as a result of the salinization process of the soils in the study area.

As a result of the high proportion of areas affected by salinity worldwide and the ecological and socio-economic effects generated by them, the dynamic estimation of these areas has shown interest for modern techniques based on remote sensing, and various models of the dynamics of saline areas have been obtained (Avdan et al., 2022; Sarkar et al., 2023; Arshad et al., 2025).

The regression analysis led to mathematical models that described the variation of the BI index in relation to the SI2 index, in the description of the Socodor area based on images in the Sentinel 2 satellite system. The correlation analysis showed a very high level of correlation between the BI and SI2 indices in each year of study, and confirms the models generated by the regression analysis. According to the multivariate analysis, the BI and SI2 indices were positioned in PC1, with a very strong, positive action, in the conditions of each year of study. This confirmed the importance and significance of the two indices for the characterization of the Socodor area, with soils affected by salinity.

CONCLUSIONS

The remote sensing technique, the Sentinel 2 system, provided relevant satellite scenes for the study, analysis and characterization of the Socodor area, Arad County, Romania, an area with soils affected by salinization. Based on the calculated indices (SI, SI2, BI and NDSI) they described in statistical terms the spatial and temporal variability, of the area affected by salinization, Socodor ATU, over the study period.

The comparative analysis showed significant differences ($p < 0.001$) between the index values during the study period. High levels of SI, SI2 and BI indices were recorded in 2022 compared to 2020 and 2024, and the NDSI index presented high values in 2020 compared to 2022 and 2024.

Among the indices calculated based on spectral data, Sentinel 2 satellite scenes, the BI and SI2 indices consistently presented a position in PC1, with very strong positive action. A very strong positive correlation was recorded between the two indices during the study period, compared to the lower level of correlation recorded between the other indices. The regression analysis led to mathematical models for estimating the variation of the BI index in relation to SI2, in conditions of statistical safety ($p < 0.001$). The recorded results indicated that these indices were more adequate in describing the study area.

The results recorded recommend the development of the study to develop more complex models for the analysis of the Socodor area by including climate data and vegetation data. The study can also be extended to other sites affected by soil salinity.

ACKNOWLEDGMENTS

The authors thank the GEOMATICS Research Laboratory, ULS "King Mihai I" from Timisoara, for the facility of the software used for this study.

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