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Seasonal spatio-temporal NDVI analysis for vegetation monitoring in Satara district of Maharashtra from 2014 to 2023

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Abstract
This study investigates vegetation dynamics in Satara district using the Normalized Difference Vegetation Index (NDVI) derived from Landsat 8 Collection 2 Level-2 satellite data over the period 2014-2023. NDVI trends were analyzed seasonally (*rabi*, summer, *kharif*) to assess inter-annual variation and spatial patterns in vegetation cover. Results revealed that NDVI was highest during the *kharif* season (0.36 to 0.54), driven by monsoonal rainfall, and lowest during summer due to high temperatures and water stress. NDVI map analysis showed the same that *kharif* seasons consistently exhibited higher vegetation cover. In contrast, *rabi* seasons showed reduced NDVI in certain years due to dependence on residual moisture and irrigation, with 2019 indicating lower vegetation and 2022 showing significantly better vegetation health. During the summer season, the eastern part of Satara persistently recorded low NDVI values, indicating recurring drought-prone conditions. Years like 2016 showed poor vegetation, while 2020 and 2022 indicated improved vegetation, likely due to effective irrigation practices. Correlation analysis indicated a strong positive relationship between NDVI and rainfall, especially in *kharif* ($r = 0.73$), followed by *rabi* ($r = 0.59$) and summer ($r = 0.50$). These findings confirm that NDVI is a robust indicator of vegetation health and seasonal climate impacts in Satara District.

Keywords: NDVI, vegetation monitoring, remote sensing, Satara district, seasonal trends

Introduction
Vegetation plays a vital role in maintaining ecological balance, supporting agricultural productivity, and regulating the hydrological cycle. Accurate monitoring of vegetation dynamics is essential for assessing ecosystem health, managing natural resources, and planning agricultural activities. Remote sensing technology has emerged as a reliable, cost-effective, and consistent approach for vegetation monitoring over large spatial and temporal scales. Satellite-based observations allow continuous assessment of vegetation health, crop conditions, and land cover changes, thereby supporting decision-making in agriculture, forestry, and environmental management.

Digital image processing of satellite data offers instruments for image analysis using various mathematical indices and algorithms. Indexes have been created to draw attention to the image's salient aspects, which are based on reflectance properties (Shikhar and Akansha., 2014) [8]. Among the various vegetation indices developed, the Normalized Difference Vegetation Index (NDVI) is the most widely adopted due to its simplicity, robustness, and strong correlation with vegetation vigour (Sahebjalal and Dashtekian, 2013) [7]. NDVI, introduced by Deering (1978) [2] and Tucker (1979) [9], ranges from -1 to +1, where values approaching +1 indicate dense and healthy vegetation, values near zero represent bare soil or built-up areas, and negative values correspond to water bodies or non-vegetated surfaces. Satara district in western Maharashtra exhibits diverse agro-climatic zones, ranging from high-rainfall regions in the west to drought-prone areas in the east. This variability, coupled with seasonal cropping patterns, makes it an ideal location for studying vegetation changes over time. This study aims to conduct a spatio-temporal analysis of NDVI from 2014 to 2023 for Satara district, assessing seasonal variations (*rabi*, summer and *kharif*) and their relationship with rainfall.

The findings will contribute to a better understanding of vegetation patterns, identify drought-prone zones, and support sustainable agricultural and resource management strategies in the region.

Materials and Methods
Study Area
Satara district is located in the western part of Maharashtra state, situated between 17°05′ to 18°11′ N latitudes and 73°33′ to 74°54′ E longitudes. The western part, particularly Mahabaleshwar, receives an average annual rainfall of over 6000 mm, while the eastern tahsils of Man, Phaltan, Khandala, and Khatav receive as little as 500 mm or less (Barakade, 2012) [1]. The eastern part of the district is particularly drought-prone. According to Pravin and Hemalata (2020) [6], out of the 11 tahsils, four (Khandala, Phaltan, Man, and Khatav) exhibit dominant drought characteristics, and one tahsil (Koregaon) is partially affected by drought.

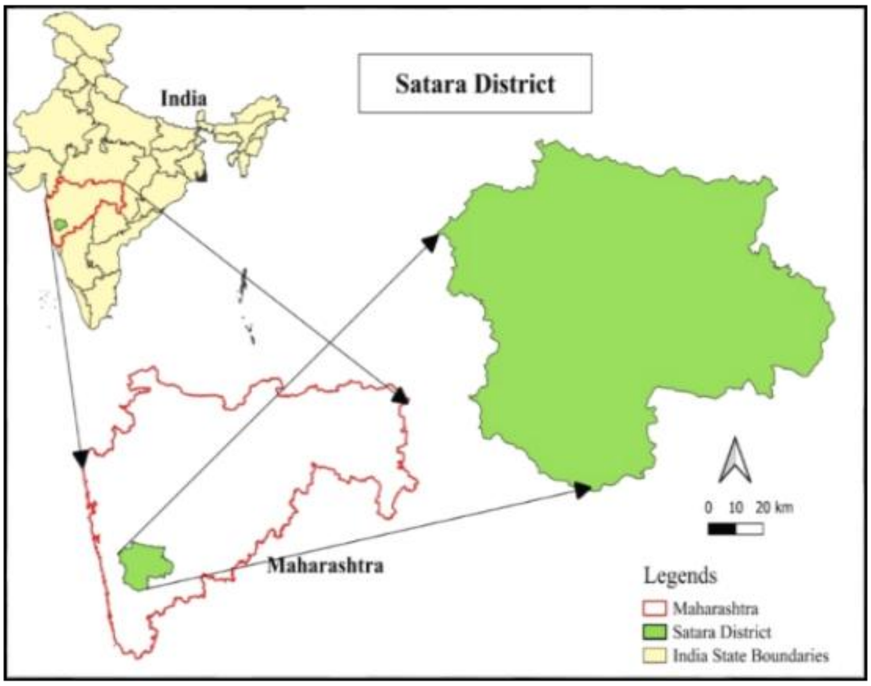


Fig 1: Location of study area-Satara District of Western Maharashtra

In this study, Landsat 8 Collection 2 Level 2 data, obtained from USGS Earth Explorer, for the period from 2014 to 2023 were used to find out NDVI using the software QGIS. NDVI is based on the principle that vegetation health reflects water availability or stress. NDVI is calculated as the ratio of the difference between the NIR and Red bands to their sum. Expressed as:
NDVI= (NIR - RED) / (NIR + RED) . . . [Deering (1978) [2], Tucker (1979)] [9+]
Where, NIR and RED are the reflectance in the near infrared and red bands.
For Landsat 8, NDVI = (Band 5 - Band 4) / (Band 5 + Band 4)
The NDVI quantifies variations in chlorophyll content (via absorption of visible red radiation) and spongy mesophyll (via reflected NIR radiation) within the vegetation canopy. Consequently, higher NDVI values typically signify greater vitality and photosynthetic activity, or "greenness," of the vegetation canopy (Tucker, 1979) [9]. Healthy vegetation reflects a significant amount of NIR radiation and absorbs much of the red light. When there is a substantial difference between reflected NIR and red radiation, the NDVI value is higher, indicating healthy, vigorous vegetation. In contrast, when the difference between NIR and red reflection is minimal, the NDVI value is lower, suggesting unhealthy vegetation or a surface that is partially or not vegetated at all.
The NDVI values range from -1 to +1 and are typically divided into four classes based on vegetation health and density, as described by Maher Milad Aburas *et al.* (2015) [4] and Sahebjalal *et al.* (2013) [7]. These classes are as follows;

Table 1: Classification of NDVI

Class	NDVI Values
Non Vegetation	< 0.1
Low Density Vegetation	0.1 to 0.2
Moderate Density Vegetation	0.2 to 0.3
High Density Vegetation	0.3 to 0.4
Very High Density Vegetation	> 0.4

Results and Discussion
Season-wise Temporal Analysis of Mean NDVI (2014-2023)
Analysis on seasonal variation of mean NDVI was carried out for the period 2014 to 2023 to examine the inter-annual variability in vegetation greenness across the, *rabi*, summer and *kharif* seasons in Satara district which is presented in Table 2 and depicted in the Fig 2.

Table 2: Seasonal Variation in Mean NDVI for Satara District (2014-2023)

Year	Mean NDVI		
	Rabi	**Summer**	***Kharif***
2014	0.30	0.27	0.46
2015	0.32	0.28	0.42
2016	0.31	0.23	0.45
2017	0.33	0.26	0.41
2018	0.31	0.26	0.42
2019	0.29	0.25	0.51
2020	0.36	0.28	0.47
2021	0.31	0.25	0.46
2022	0.37	0.28	0.50
2023	0.29	0.29	0.49

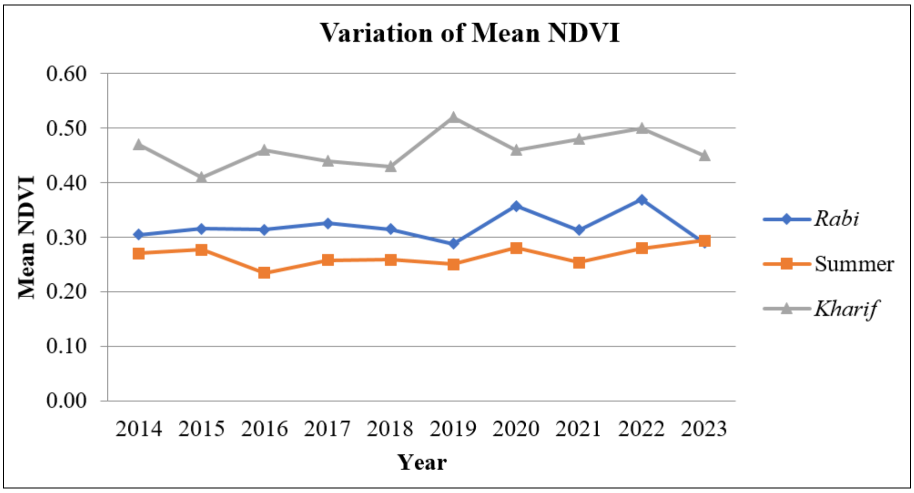


Fig 2: Variation of mean NDVI during *rabi*, summer and *kharif* for Satara District (2014-2023)

The temporal variation in mean NDVI values during the *rabi* season for Satara district from 2014 to 2023 shows noticeable inter annual fluctuations. The mean NDVI ranged from 0.29 to 0.37, indicating moderate vegetation vigour throughout the study period. The lowest NDVI values were recorded in 2019 (0.29) and 2023 (0.29), suggesting reduced vegetation activity during these years. In contrast, the highest NDVI value was observed in 2022 (0.37), followed closely by 2020 (0.36), indicating healthier vegetation conditions and more favourable crop growth during these periods.

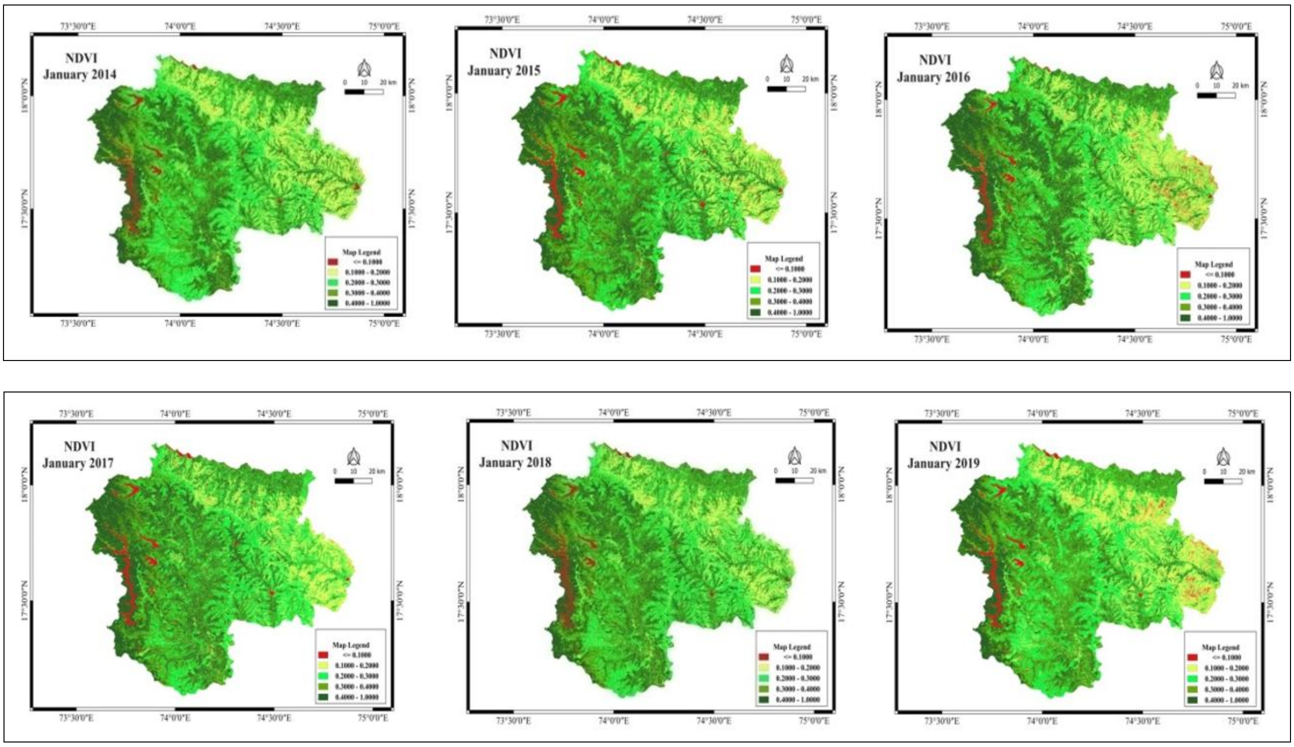
In the summer season, the NDVI values were consistently low in every years, ranging from 0.23 (2016) to 0.29 (2023). The years 2015, 2020, and 2022 recorded higher NDVI values (0.28), while 2016 had the lowest NDVI (0.23), revealing the least vegetation cover during that season.

Mean NDVI values for *kharif* ranged from 0.41 (2017) to 0.51 (2019), exhibiting more robust vegetation growth during this monsoon-driven cropping season. 2019 recorded the highest NDVI (0.51), followed by 2022 (0.50) and 2023 (0.49).The years 2015, 2017, 2018 displayed comparatively lower values of mean NDVI ranging from 0.41 to 0.42

Season-wise Spatial Assessment of NDVI Using Thematic Maps (2014-2023) for Satara District

Fig 3 to 5 represents the spatial variability of vegetation condition in Satara district evaluated using NDVI thematic maps across *rabi*, *kharif*, and summer seasons from 2014 to 2023.

***Rabi* season**



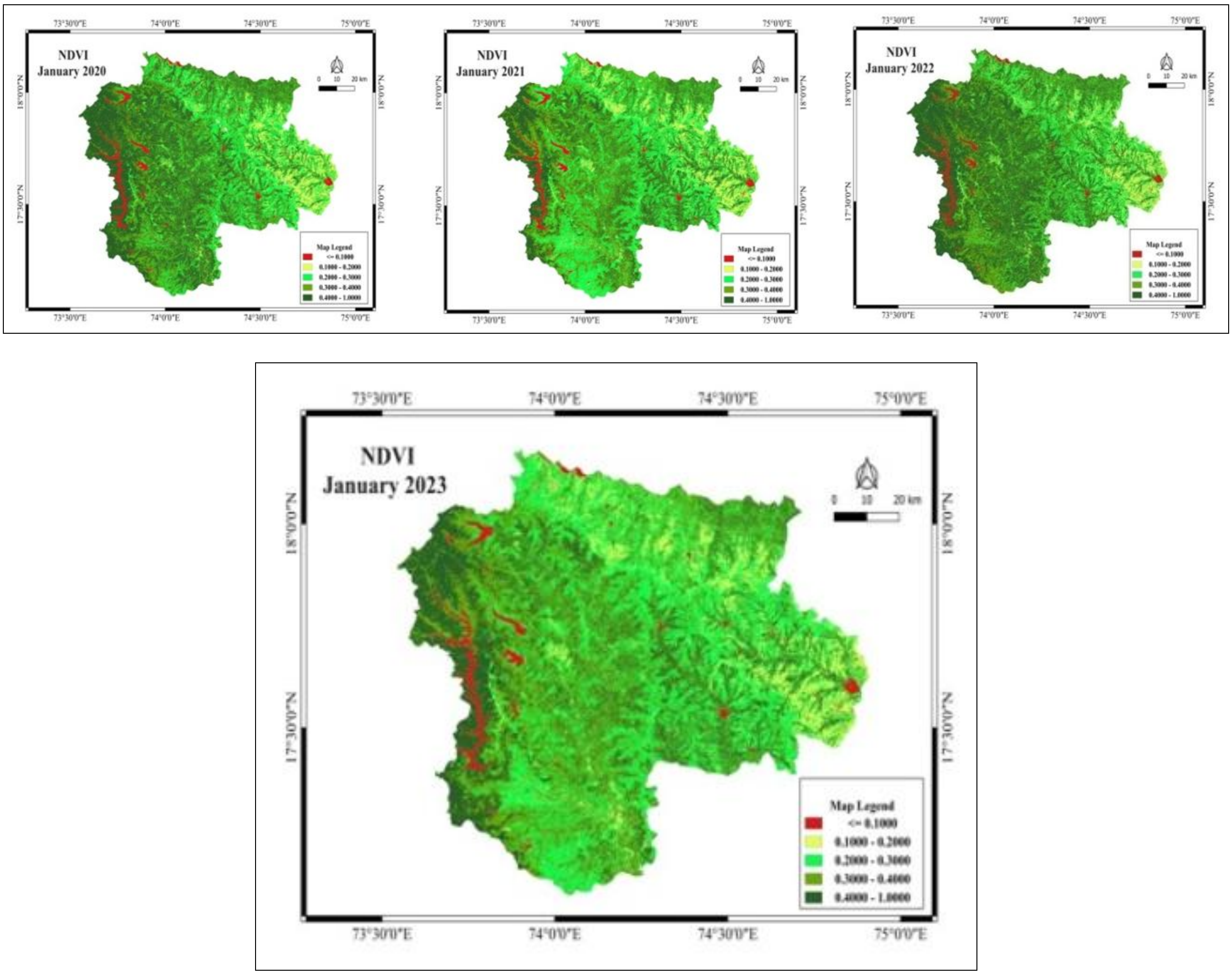
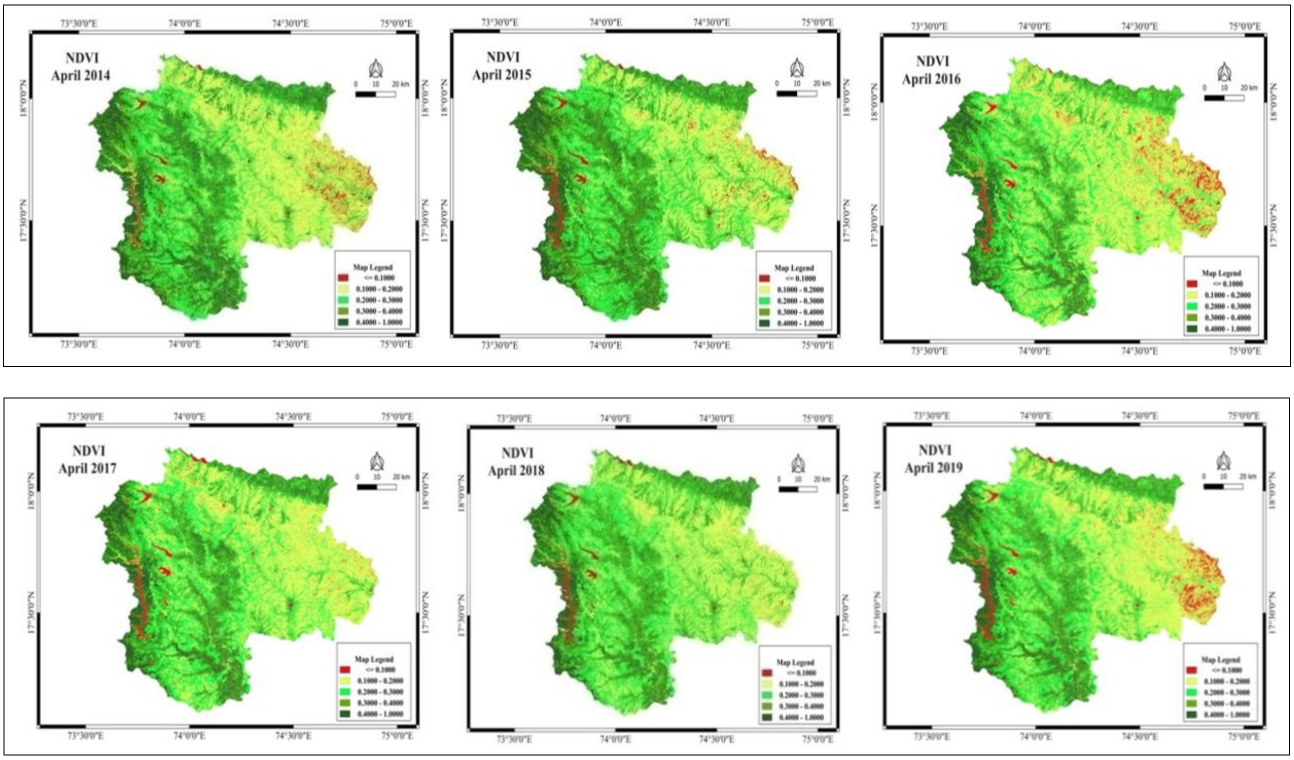


Fig 3: Seasonal NDVI map during *rabi* season for Satara District (2014-2023): January representation

Summer Season



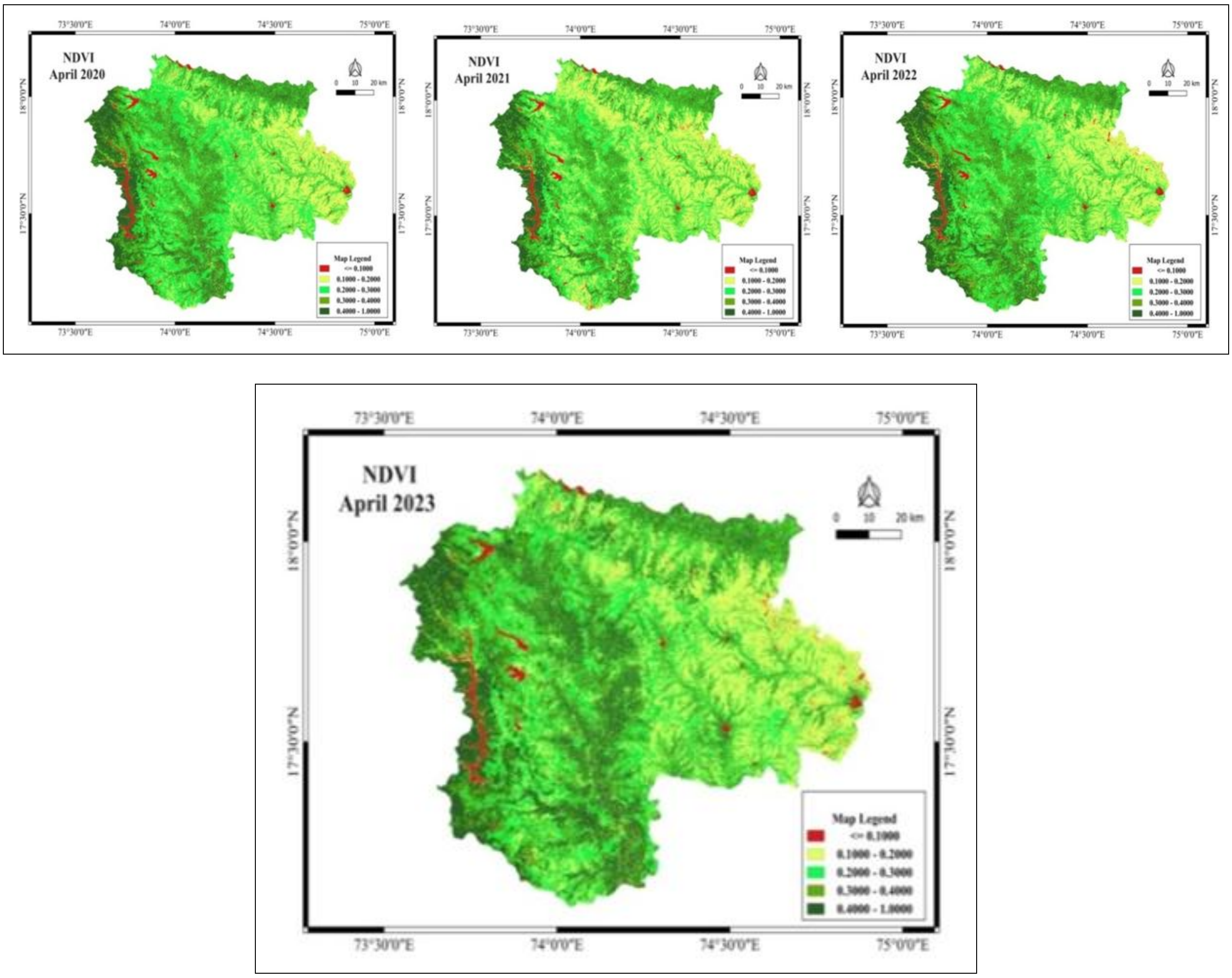
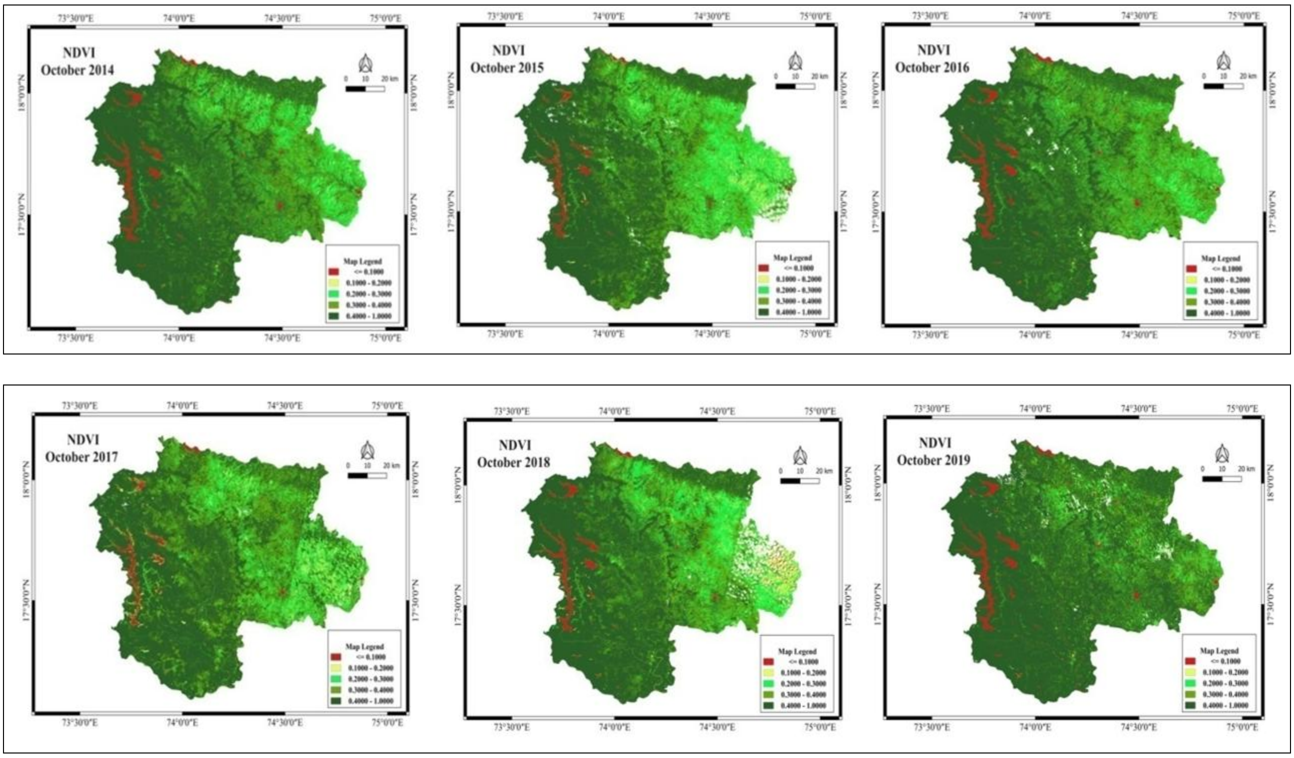


Fig 4: Seasonal NDVI map during summer season for Satara District (2014-2023): April representation

Kharif Season



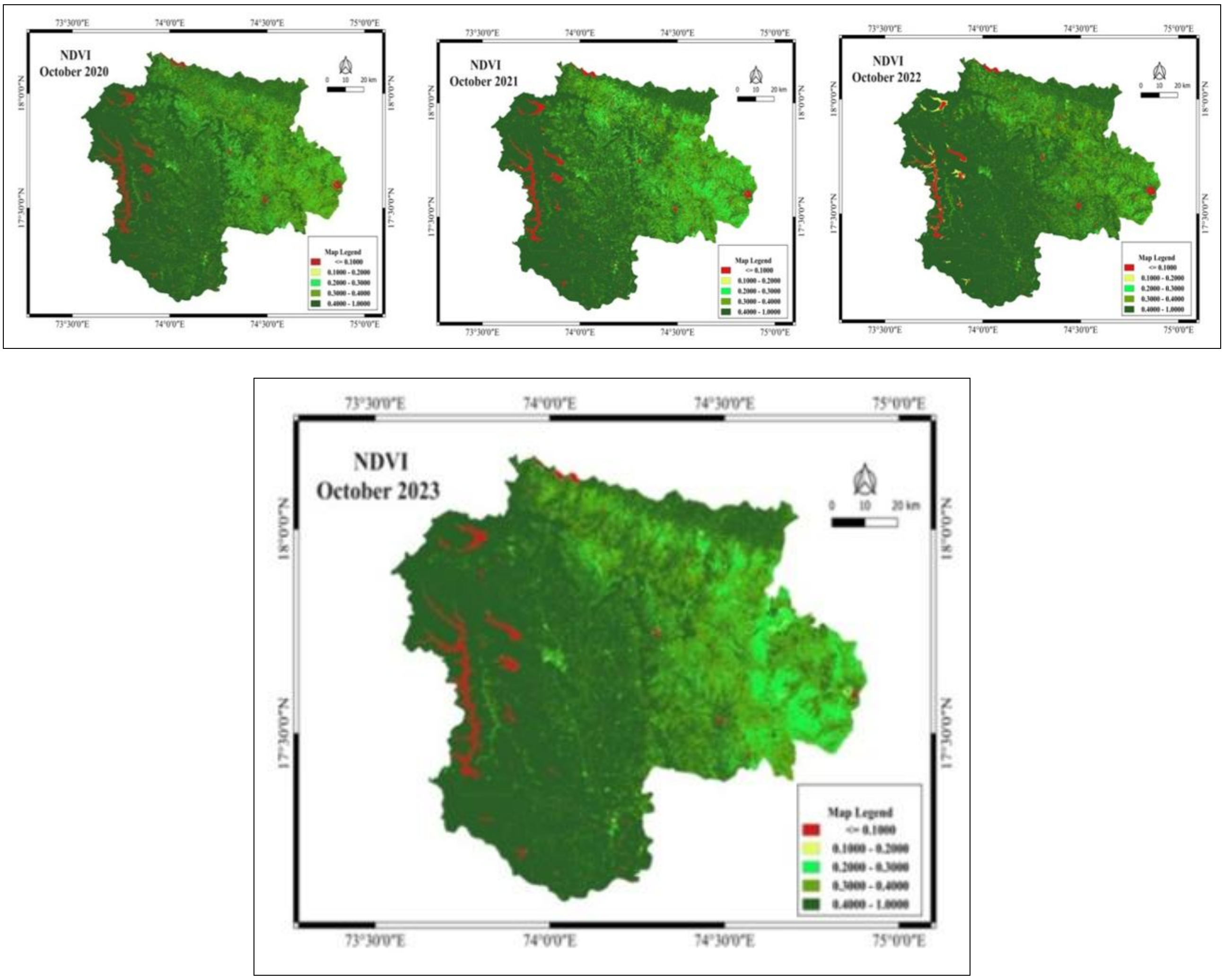


Fig 5: Seasonal NDVI map during *kharif* Season for Satara District (2014-2023): October representation

Significant seasonal and inter annual fluctuations in the vegetation cover throughout the Satara district were found by spatially analyzing NDVI maps throughout various seasons. During the *rabi* season, 2019 exhibited relatively lower vegetation cover, whereas 2022 showed a higher vegetation response, indicating favourable growing conditions during that year. In the summer season, vegetation cover was overall lower compared to *rabi*, with drought-prone areas being prominently observed in the eastern parts of the district. Notably, 2020 and 2022 recorded better vegetation cover during summer, while 2016 experienced the least vegetation greenness. In the *kharif* season, vegetation cover was significantly higher than in the other two seasons. The NDVI maps for 2019 showed widespread and dense vegetation, while 2015 exhibited comparatively lower greenness. Across the *kharif* seasons, the maps showed consistent vegetation cover throughout the district, reflecting the positive influence of monsoon rainfall.

Seasonal Area-wise Classification of Vegetation Using NDVI in Satara District (2014-2023)

The area-wise classification of vegetation using NDVI during the *rabi* season (2014-2023) is presented in Table 3 and illustrated in Figure 6.

Table 3: Percent Area Classified Based on NDVI-Derived Vegetation Density in Satara District during *Rabi* Season (2014-2023)

Year	Non Vegetation (%)	Low Density Vegetation (%)	Medium Density Vegetation (%)	High Density Vegetation (%)	Very High Density Vegetation (%)	Total (%)
2014	2.52	16.57	30.90	24.26	25.75	100
2015	2.71	16.34	25.85	25.65	29.44	100
2016	2.98	18.85	26.23	22.31	29.63	100
2017	2.47	14.25	30.28	23.31	29.69	100
2018	2.56	12.92	31.13	25.95	27.45	100
2019	2.97	20.35	31.72	25.38	19.58	100
2020	2.71	7.89	25.57	25.03	38.79	100
2021	2.62	9.23	32.85	30.42	24.87	100
2022	2.82	7.12	20.47	26.54	43.05	100
2023	2.62	8.73	34.57	30.79	23.30	100

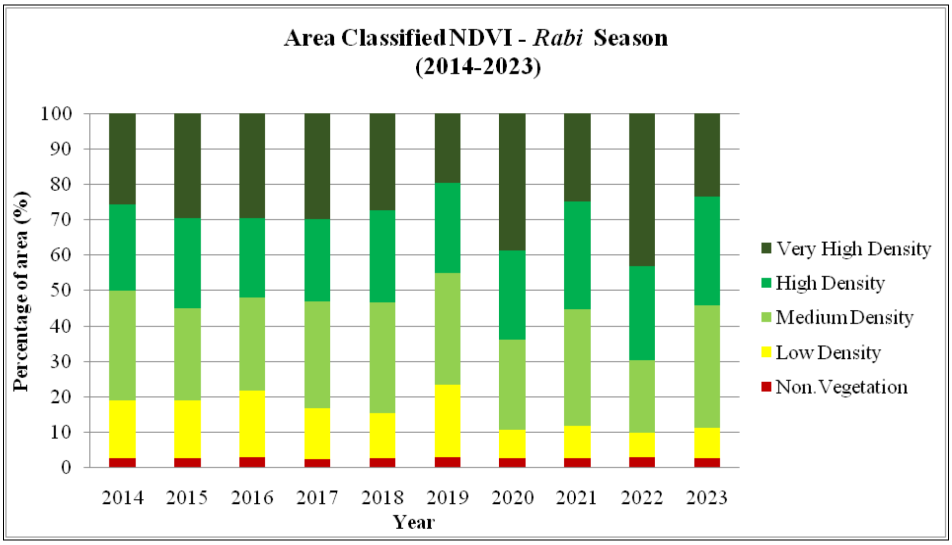


Fig 6: Percent area classified NDVI during *rabi* season for Satara District (2014-2023)

Analysing the Table 3 and Fig 6 the non-vegetation class remained relatively constant throughout the decade, fluctuating slightly between 2.47% (2017) and 2.98% (2016), and indicating minimal change in barren land and the water bodies. The low-density vegetation category showed notable shifts, ranging from 7.12% in 2022 to a high of 20.35% in 2019, suggesting variations in sparse vegetation cover likely influenced by climatic and agronomic conditions. Medium-density vegetation also experienced considerable change, with its lowest share in 2022 (20.47%) and the highest in 2023 (34.57%). A steady increase in the high-density vegetation category was observed in the later years, peaking at 30.79% in 2023, followed by 30.42% in 2021. The very high-density vegetation class demonstrated the widest range among all categories, reaching a minimum of 19.58% in 2019 and a maximum of 43.05% in 2022, highlighting the varying extent of dense and healthy vegetation across different years.

The area-wise classification of vegetation using NDVI during the summer season (2014-2023) is presented in Table 4 and illustrated in Figure 7.

Table 4: Percent Area Classified Based on NDVI-Derived Vegetation Density in Satara District during Summer Season (2014-2023)

Year	Non Vegetation (%)	Low Density Vegetation (%)	Medium Density Vegetation (%)	High Density Vegetation (%)	Very High Density Vegetation (%)	Total (%)
2014	3.01	34.76	27.23	16.93	18.08	100
2015	3.14	28.09	31.04	19.96	17.77	100
2016	4.75	42.98	27.83	12.72	11.71	100
2017	2.32	38.02	30.86	14.60	14.19	100
2018	2.25	33.51	33.54	17.22	13.49	100
2019	4.09	38.11	28.95	14.74	14.10	100
2020	2.28	23.65	36.85	19.81	17.42	100
2021	2.31	34.68	33.08	17.20	12.73	100
2022	2.09	24.73	35.14	21.78	16.27	100
2023	2.12	26.74	30.62	18.44	22.09	100

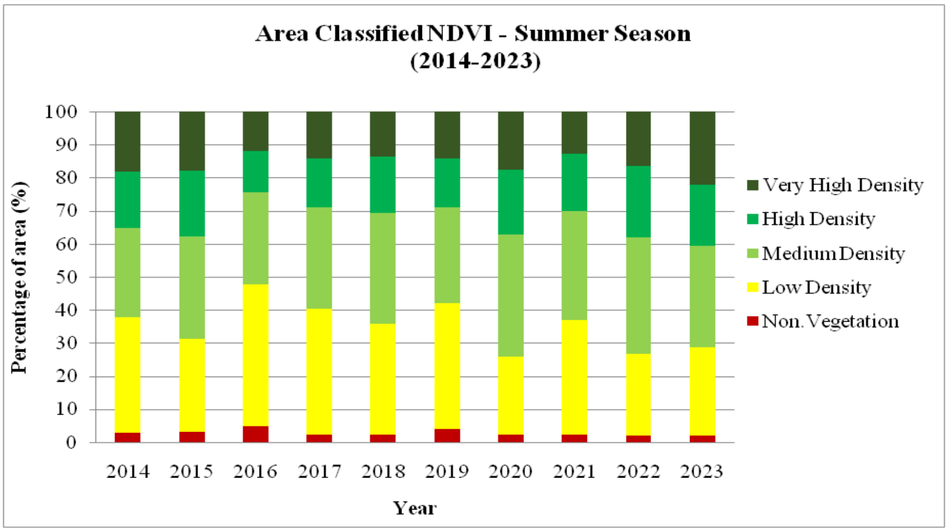


Fig 7: Percent area classified NDVI during summer season for Satara District (2014- 2023)

From the Table 4 and the Figure 7 it is clear that the vegetation classification based on NDVI for the summer season in Satara district revealed year-to-year shifts across all vegetation density categories. The non-vegetated area showed limited fluctuations, ranging from 2.09% in 2022 to 4.75% in 2016, indicating relative stability in barren or built-up land cover. Low-density vegetation was most prominent in 2016 (42.98%), followed by higher values in 2017 and 2019, reflecting increased presence of sparsely vegetated zones during those years. Conversely, years like 2020 and 2022 recorded significantly lower percentages in this class, pointing to comparatively healthier vegetation. Medium-density vegetation maintained a moderate range across the period, peaking at 36.85% in 2020 and reaching its lowest in 2014 (27.23%). A similar trend was observed in high-density vegetation, with values improving over time and culminating in 21.78% in 2022, whereas 2016 recorded the least at 12.72%. The very high-density vegetation category, though generally lower in earlier years, saw notable growth by 2023, reaching 22.09%, suggesting improved vegetation vigor in recent times.

The area-wise classification of vegetation using NDVI during the *kharif* season (2014-2023) is presented in Table 5 and illustrated in Figure 8.

Table 5: Percent Area Classified Based on NDVI-Derived Vegetation Density in Satara District during *Kharif* Season (2014-2023)

Year	Non Vegetation (%)	Low Density Vegetation (%)	Medium Density Vegetation (%)	High Density Vegetation (%)	Very High Density Vegetation (%)	Total (%)
2014	2.36	1.59	12.11	19.46	64.47	100
2015	1.85	3.56	17.13	21.99	55.47	100
2016	2.32	1.51	11.73	22.12	62.32	100
2017	1.19	2.86	12.05	27.60	56.30	100
2018	2.33	3.95	14.48	20.36	58.88	100
2019	2.69	1.11	5.66	14.82	75.71	100
2020	2.56	0.78	7.17	21.12	68.37	100
2021	2.01	1.67	11.13	23.15	62.04	100
2022	1.86	1.24	4.62	15.62	76.66	100
2023	2.17	0.84	9.21	18.20	69.58	100

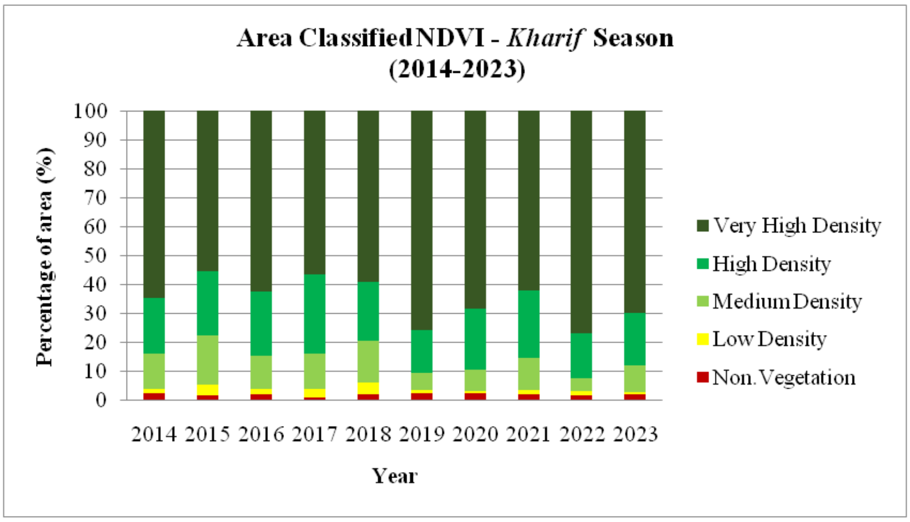


Fig 8: Percent area classified NDVI during *kharif* season for Satara District (2014-2023)

Vegetation distribution during the *kharif* season in Satara district revealed a consistent dominance of high to very high-density vegetation across the ten-year period. According to the Table 5 and the Figure 8 the non-vegetation class remained minimal, fluctuating narrowly between 1.19% (2017) and 2.69% (2019), suggesting limited barren or built-up land during this peak growing season. The low-density vegetation class was also minimal throughout, with the lowest recorded in 2020 (0.78%) and the highest in 2018 (3.95%), indicating sparse vegetation presence. Medium-density vegetation ranged from 4.62% (2022) to 17.13% (2015), with notable drops in years like 2019 and 2022, suggesting improved or diminished vegetation vigour, respectively. High-density vegetation remained moderately distributed, peaking at 27.60% in 2017, and was lowest in 2019 (14.82%). The very high-density vegetation category dominated in most years, contributing more than 55% of the total area, with the highest recorded in 2022 (76.66%), followed by 2019 (75.71%), highlighting lush and vigorous vegetation cover during favourable monsoon periods.

The seasonal NDVI-based vegetation classification over the ten-year period (2014-2023) in Satara district reveals significant variation in vegetation density influenced by seasonal weather patterns and agricultural practices. The *kharif* season consistently recorded the highest proportion of very high-density vegetation, often exceeding 60%, reflecting the strong influence of monsoonal rainfall and active cropping during this period. In contrast, NDVI values during the summer season were relatively low, with a larger share of land falling under low to medium-density vegetation classes, indicating limited vegetative activity due to high temperatures and low soil moisture availability. The *rabi* season displayed moderate vegetation cover, varying across years based on residual soil moisture and irrigation inputs.

These findings align with the observations of Patil *et al*. (2024) [5], who reported that NDVI values tend to be lowest during the summer and highest in the *kharif* season, confirming the seasonal dependence of vegetation vigour in semi-arid regions. The dynamic shifts in vegetation density classes across seasons underscore the importance of timely water availability, cropping calendars, and land management strategies in sustaining agricultural productivity.

Table 6: Year-Wise Trends in Vegetation Indices and Rainfall During *Rabi*, Summer and *Kharif* Season for Satara District (2014-2023)

Year	*Rabi*		Summer		*Kharif*	
	Mean NDVI	Rainfall (mm)	Mean NDVI	Rainfall (mm)	Mean NDVI	Rainfall (mm)
2014	0.30	20.6	0.27	13.6	0.47	666.4
2015	0.32	1.9	0.28	69.6	0.41	317.2
2016	0.31	0.7	0.23	6.7	0.46	688.3
2017	0.33	0.0	0.26	25.7	0.44	984.2
2018	0.31	19.7	0.26	2.9	0.43	599.2
2019	0.29	37.7	0.25	11.4	0.52	1303.2
2020	0.36	12.8	0.28	39.6	0.46	940.0
2021	0.31	6.6	0.25	38.0	0.48	838.9
2022	0.37	156.6	0.28	60.6	0.50	812.9
2023	0.29	3.0	0.29	20.3	0.45	403.0

Table 7: Rainfall-NDVI correlation by season

Season	Correlation Coefficient (r)
Rabi	0.59 (p=0.07*)
Summer	0.50 (p=0.14)
Kharif	0.73 (p=0.01**)

Note: *$p< 0.1$, **$p< 0.05$.

Rainfall and NDVI showed a positive association across all three seasons (Table 7), with the strongest correlation during kharif (r = 0.73, $p< 0.05$, significant at 5% or 0.05), followed by rabi (r = 0.59, $p< 0.1$, significant at 10% or 0.1) and summer (r = 0.50, not significant even at 10%). This pattern highlights the critical role of monsoonal precipitation in vegetation development and aligns with the findings of Himanshu *et al.* (2015) [3], who reported a strong linear relationship between rainfall and NDVI.

Summary

This study focuses on analyzing the spatial and temporal vegetation conditions in Satara district situated in the western region of Maharashtra using vegetation indices derived from satellite imagery. Landsat 8 Collection 2 Level-2 data, known for its accurate surface reflectance corrections, was employed for a 10-year period (2014-2023). The analysis was conducted for three major crop-growing seasons: *rabi*, summer, and *kharif*, with NDVI maps of January, April and October representing these seasons, respectively.

NDVI is computed to assess vegetation health. Thematic maps illustrated the inter-annual and seasonal variations, and correlation analysis was performed with rainfall to understand its influence on vegetation. The seasonal mean variation showed that NDVI was highest during *kharif* and lowest in summer, indicating better vegetation in the monsoon and poor cover in dry months.

Across all seasons and years, the eastern region of Satara consistently showed lower NDVI values, identifying it as a vulnerable and drought-prone zone requiring targeted intervention.

NDVI analysis revealed that *kharif* seasons consistently exhibited higher vegetation cover, driven by adequate monsoon rainfall. In contrast, *rabi* seasons showed reduced NDVI in certain years due to dependence on residual moisture and irrigation, with 2019 indicating lower vegetation and 2022 showing significantly better vegetation health. During the summer season, the eastern part of Satara persistently recorded low NDVI values, indicating recurring drought-prone conditions. Years like 2016 showed poor vegetation, while 2020 and 2022 indicated improved vegetation, likely due to effective irrigation practices.

NDVI showed a substantial positive association with precipitation in all three seasons, especially in *kharif* (r = 0.73), followed by *rabi* (r = 0.59) and summer (r = 0.50), highlighting the critical role of precipitation in vegetation development.

Conclusion

The analysis of mean NDVI across *rabi*, summer, and *kharif* seasons over a ten-year period (2014-2023) clearly illustrates the seasonal dynamics of vegetation health in Satara district. The *kharif* season consistently exhibited higher mean NDVI values, indicating dense and healthy vegetation cover due to favourable monsoon rainfall. In contrast, the summer season recorded the lowest NDVI values, reflecting scarce vegetation and dry soil conditions.

Analysis of the NDVI maps revealed that the eastern part of Satara district consistently experienced low vegetation cover and higher drought severity throughout the study period. This pattern was particularly noticeable in the summer, indicating that this region is particularly vulnerable to seasonal drought stress and may require focused water conservation and agricultural management interventions. From the NDVI maps and area classification, *rabi* 2019 was marked by the least vegetation cover, while 2022 had the most extensive vegetation. In the summer season, 2014 showed very low vegetation density, indicating severe drought and 2023 recorded high vegetation density, suggesting improved conditions. During *kharif*, NDVI maps highlighted 2015 as a drought-impacted year, while 2019 demonstrated strong vegetation growth.

Across all seasons, NDVI exhibited a positive correlation with rainfall, with the strongest association observed during the *kharif* season, indicating greater vegetation responsiveness to precipitation in this period.

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