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RESEARCH

Burned area assessment using Sentinel-2A satellite imagery and DNBR spectral index (Case study: forest areas on the anticline in the Khaiz region, Iran)

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The main advantage of incorporating remote sensing techniques into wildfire management is their ability to provide real-time data. This study aimed to investigate the extent of forest fires in southwestern Iran using remote sensing data. Sentinel-2A data with a resolution of 20 meters were used to conduct this study. It is worth noting that the spectral bands selected in this study, namely spectral band 8A (red edge 4) and band 12 (SWIR 2), have proved their suitability for fire intensity classification. In this study, ΔNBR (Normalized Burn Ratio) values within the study area ranged from −0.096 to 0.81. These values were categorized based on the United States Geological Survey classification table. The study area covered 4,758.915 hectares, with approximately 32.41% (1,542.284 hectares) having calculated ΔNBR values. Of the total area, 60.97% (2,901.675 hectares) was burned at low intensity, while approximately 6.62% (314.956 hectares) was burned at medium intensity. Unfortunately, due to the limited extent of the study area, regions with moderate to high fire intensity and high intensity were not included in the classification. The research results indicate that the studied index has satisfactory efficiency. The application of this index to regions with characteristics similar to those of the Khaiz anticline is likely to provide valuable and reliable results.

Keywords: remote sensing, dNBR index, sentinel-2A imagery, Khaiz mountain range

1. Introduction

Fires a central role in triggering environmental change and have both local and regional impacts (1). Whether triggered by anthropogenic activities or natural factors, wildfires can have profound and catastrophic consequences for ecosystems (2).

Destroying these critical stands of trees, which are essential to our well-being, has negative impacts such as landslides, erosion, and igniting desertification, all of which are triggered by conflagration(1). Fires cause seismic disturbances in the soil structure and alter landscape topography, reshaping ecosystem functions (Rosa et al. 2018). Such changes also disrupt moisture levels, as fires often lead to biomass decomposition and carbon emissions, causing shifts in native climate (2).

The effects of these fires include partial or complete loss of vegetation cover, which affects physical properties of the soil, reduces biological vitality, increases surface runoff, and allows uncontrolled runoff downstream (1). In addition, these fires cause sudden flooding and make the soil more susceptible to water erosion, increasing sediment accumulation (Rosa et al. 2018). The total destruction of vegetation has serious and permanent consequences, such as the darkening of tree canopies and the impairment of root systems (2).

Fire severity encompasses the multiple ecological changes that occur after a fire event (Sabhani et al. 2021). This construct consists of two key dimensions: the degree of soil involvement and the complicated interactions with vegetation and the surrounding environment (2). In Iran and several other regions of the world, Earth observation using satellite technology is widely used for burned area detection (BA) and ongoing fire monitoring (Sabhani et al. 2021).

Identification of active fires relies primarily on the influence of fire on vegetation reflectance, while detection of ongoing fires depends on the detectable thermal contrast between the fire and the background (Rotta et al. 2019).

Today, remote sensing has solidified its position as an indispensable tool for monitoring, analyzing, and rehabilitating fire-affected regions on both global and regional scales (3). Rapid mapping using remote sensing not only provides rapid results, but also proves to be more cost-effective than manual calculations (4). The spectral index-based approach is a widely accepted method because of its ease of implementation and the remarkable precision it provides in detecting burned areas (5). Satellite-derived products delineating burned areas are essential for several research objectives (Sabhani et al. 2021). The study of spectral changes in the near-infrared (NIR) and shortwave infrared (SWIR) spectral ranges plays a prominent role in most mapping of burned areas (6). In the NIR spectral region, changes in canopy cover and radiation intensity attributable to foliage burning predominate, while changes in landscape dryness are mainly seen in the SWIR spectral region (7).

Reflectance of vegetation, especially in the NIR and SWIR spectral regions, shows clear differences between undamaged vegetation and burned zones (6). It is significant that these spectral regions show a marked decrease in NIR reflectance and an increase in SWIR reflectance after a fire event (2).

The first effect is primarily attributed to the sensitivity of the near-infrared (NIR) band to chlorophyll content in healthy vegetation, while the second effect is associated with the modulation of soil moisture and vegetation cover to shortwave infrared (SWIR) reflectance (8). It should be noted, however, that spectral indices may exhibit variations that depend on the specific location and time of observation (6). Spectral band ratios, which often include NIR and SWIR wavelengths that are less susceptible to atmospheric interference, are considered common indicators (Hian et al. 2016). In recent years, Sentinel-2A has gained wide recognition in the remote sensing community due to its many improved features, including wider spectral bands, lower geometric distortions, higher spatial and spectral resolution, and an open data policy (2). Although both Landsat-8 OLI and Sentinel-2A MSI have shown promise for various applications, there is an ongoing debate about which satellite is better for fire severity assessment (6).

In recent years, various researchers both in Iran and around the world have conducted a wealth of research focused on identifying, monitoring, and analyzing fire behavior through the use of satellite imagery and the integration of geographic information systems (GIS). These efforts have led to the formulation of optimized algorithms that enable accurate fire detection at both global and regional scales (Sabhani et al. 2021). A study conducted by Atak and Tonyaloglu (9) serves as a prime example of the use of spectral indices to estimate burned areas, as demonstrated in the case of Izmir, Turkey, following a fire incident on August 18, 2019. In this study, sentinel imagery was used to delineate burned and unburned areas and to create a reference dataset. Spectral indices such as NDVI, ARVI, NBR, NBR2, and BAI were calculated using two Landsat 8 satellite images acquired on August 7 and 28, 2019 (Sabhani et al. 2021) and Bahadir et al. (16).

Moura et al. (2) and Efthimiou et al. (17) conducted a comprehensive study to assess the intensity of forest fires and subsequent regrowth in affected regions of Chapada Diamantina National Park in Bahia, Brazil. This assessment was facilitated by the use of spectral indices, namely dNBR and RdNBR. The results highlighted the central role of these indices as invaluable tools for classifying burned areas and assessing post-fire vegetation recovery, depending on the specific parameters of the study area (8).

A fire event occurred in the Khaiz anticline from May 28 to June 2, 2020. Given the large geographic area and logistical challenges associated with the region, the application of remote sensing techniques in this study area is of great importance. The main objective is to independently delineate the burned area, categorize the extent of fire severity, and identify the spatial distribution of fire intensity using the Differenced Normalized Burn Ratio (DNBR) spectral index.

2. Area of study

The Khaiz anticline, which extends over a length of about 42 kilometers and an average width of about 4.5 kilometers, is oriented in a northwest–southeast direction and is located within the southern sector of the Bangistan anticline (10) (**Figure 1**). Geographically, this area straddles the border of Khuzestan province in the north and northeast of Behbahan city and Kohgiluyeh and Boyer Ahmad in the south and southwest of Dehdasht city, as indicated on Map 1 (18).

The Khaiz anticline is divided into western and eastern segments by the Maron River and includes geological formations such as the Late Cretaceous Gorpi, the Eocene Pabdeh, the Oligo-Miocene Asmari Limestone, and the Fourth-Age Alluvium (10).

Due to the geological pressure and resistance of the Asmari limestone, the Khaiz anticline has numerous fractures, faults, and corrosion features. The region has an average annual temperature of 22.7 degrees Celsius and an average annual precipitation of 254.6 degrees Celsius. According to Demarten's classification, the area falls into the semiarid category (18). The structure of the Khaouiz anticline,

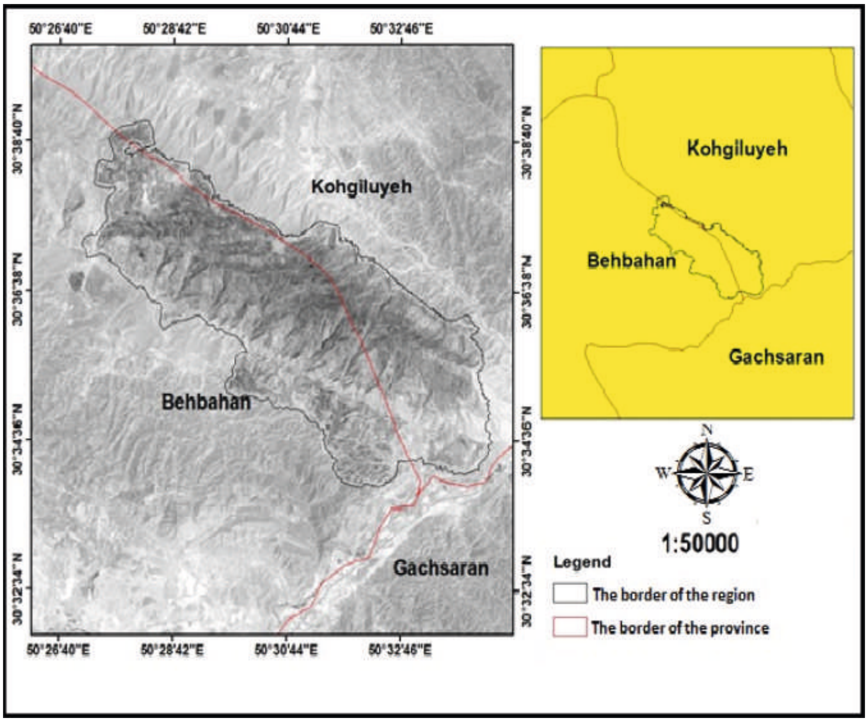

FIGURE 1 | Location of the study area in Khuzestan and Kohgiluyeh province.

TABLE 1 | Image specifications.

Acquisition	Image code/source	Fire status	Instrument	Satellite System
17/05/2020	L1C_T39RVP_A025600_20200517T072346	Pre – Fire	MSI	Sentinel-2
6/6/2020	L1C_T39RVP_A025886_20200606T072119	Post – Fire		

TABLE 2 | Sentinel-2 image specifications.

Sensor	Spatial Resolution (m)	Kanal	Julat Spectral	Wavelength range (μ m)
Sentinel-2A				
MSI	10	Band 2	Blue	0.49
		Band 3	Green	0.56
		Band 4	Red	0.665
		Band 8	NIR	0.842
	20	Band5	Red edge1	0.705
		Band6	Red edge2	0.74
		Band7	Red Edge 3	0.783
		Band 8A	Red Edge 4	0.865
		Band 11	SWIR	1.61
		Band 12	SWIR	2.19
	60	Band 1	Coastal aerosol	0.443
		Band 9	Water vapor	0.945
		Band 10	SWIR—Cirrus	1.375

influenced by the geological pressure and the elasticity of the Asmari limestone, has led to the formation of a large number of fissures, seams, and 24 corrosion faults. The local climate is characterized by an average annual temperature of 22.7 degrees Celsius and an average annual precipitation of 254.6 millimeters. According to the classification of

Demarten, this region falls into the category of semi-arid areas (10).

3. Research methodology

The use of remote sensing technology combined with the availability of imagery has greatly improved the mapping of burned areas through the application of spectral indices, ensuring a high degree of precision (Rafael et al. 2021).

A limitation of low spatial resolution sensors is that they are unable to detect spectrally mixed pixels (2). Uncertainties significantly affect the accuracy of wildfire mapping, which affects detection algorithms (Sabhani et al. 2021). Therefore, sensors such as Sentinel-2, which are known for their high-precision capabilities, remain essential (Hiya Yan et al. 2020).

Sentinel-2's potential for fire mapping remains underexplored despite its improved spatial resolution (10–60 m resolution with 13 bands) compared to many medium-resolution sensors (Rafael et al. 2021). Notably, Sentinel-2 offers imagery within the red edge band, crucial for vegetation monitoring due to its sensitivity to chlorophyll changes. This sensitivity proves particularly valuable in identifying burned areas using vegetation cover spectral indices. Moreover, most red-edge-utilizing vegetation spectral indices outperform non-red-edge variants. For instance, Filipponi's research indicates that Sentinel-2's Burnt Area Index (BAI2) excels in spectral discrimination of burned areas compared to other indices (Hiya Yan et al. 2020).

Sentinel 2 encompasses two satellites, Sentinel 2A and 2B, with Sentinel-2A launched in June 2015 and Sentinel-2B in July 2016 (11). The MSI configuration includes 13 spectral bands. The launch of Sentinel-2A alongside Sentinel-2B carrying the MSI multispectral instrument creates a platform

TABLE 3 | Spectral indices.

Spectral index	Abbreviation	Formula
Normalized burn ratio	NBR	(NIR-SWIR2)/(NIR-SWIR2)
Difference normalized burn ratio	dNBR	NBR pre-fire—NBR post-fire

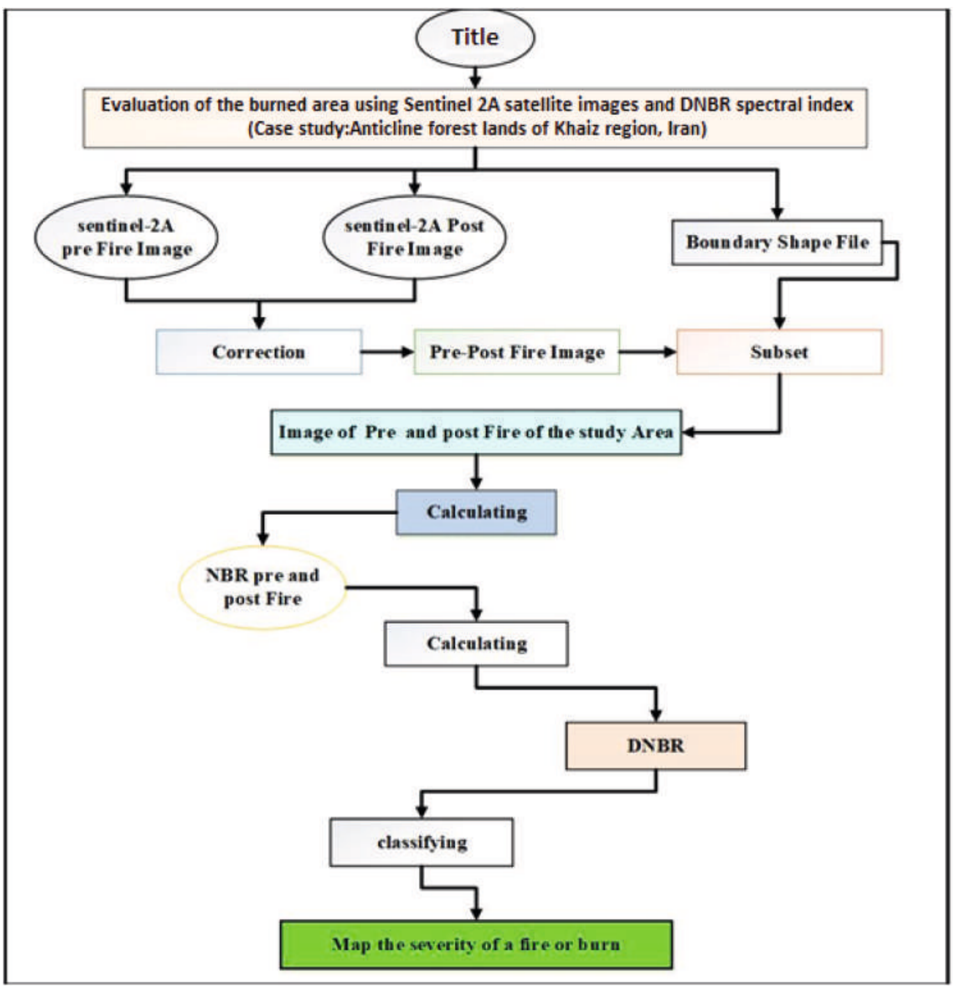

FIGURE 2 | Flowchart of information processing steps for mapping burned areas using medium spatial resolution (Hiya Yan et al. 2020). The combination of high temporal resolution and medium spatial resolution facilitates effective monitoring of rapid land cover changes like fires, floods, and volcanic eruptions (12). Recent investigations employing Sentinel-2 spectral indices demonstrate strong correlations with burned areas and the degree of burn intensity, as assessed through fieldwork (Rafael et al. 2021). The data presented in this research (**Table 1**), sourced from the US Geological Survey website, were utilized for burned area mapping and the determination of burn severity. Spectral indices were applied using both spectral and spatial information (**Table 2**).

4. Spectral indicators

Spectral indices, a common fire assessment tool, primarily involve quantifying spectral pattern variations in satellite imagery acquired before and after a fire event (13). These indices have an inherent sensitivity to changes often caused by fires (14). Among the well-known indices in this category, the Normalized Burn Ratio (NBR) stands out, known for its usefulness in delineating fire-affected regions in large areas (Liorens et al. 2021).

The mathematical formulation for calculating the NBR is very similar to that of the Normalized Difference Vegetation Index (NDVI) (14). The main difference is that both near-infrared (NIR) and shortwave-infrared (SWIR) wavelengths are considered. In healthy vegetation, the NIR spectral region has a significantly increased reflectance, while the SWIR region has a significantly lower reflectance, which is a marked difference from the characteristics observed in fire-ravaged areas (13).

As a result, areas that have experienced recent fires exhibit elevated levels of NIR reflectance and reduced levels of SWIR reflectance (15). This phenomenon contributes to the most

TABLE 4 | Burn intensity level resulting from dNBR calculation, suggested by USGS.

Severity Level	dNBR range (scaled 103)	dNBR (not scaled)
Enhanced Regrowth, high	–500 to –251	−0.500 to −0.251
Enhanced Regrowth, low	−250 to −101	−0.250 to −0.101
Unburned	−100 to + 99	−0.100 to 0.099
Low Severity	+ 100 to + 269	0.100 to 0.269
Moderate – low Severity	+ 270 to +439	0.270 to 0.439
Moderate– high Severity	+ 440 to +659	0.440 to 0.659
High Severity	+ 660 to +1300	0.660 to 1.300

significant distinction in spectral responses observed between areas of thriving vegetation and fire-affected regions across the NIR and SWIR segments of the electromagnetic spectrum (13). The operational principle of the Normal Burn Ratio (NBR) hinges on assessing the relative sensitivities of the NIR band to the condition and structure of plant cells, in comparison with the sensitivities of the SWIR band to the presence of plant cellulose and water content. NBR values generally span from −1 to + 1 (14). A heightened NBR value is indicative of vibrant vegetation, while a diminished value signifies regions affected by fire (15).

The utilization of the NBR index is most applicable in regions where vegetation is anticipated to experience gradual regeneration (13). However, its efficacy could be diminished in areas characterized by high humidity and rapid vegetation growth, such as tropical regions (14). It is important to acknowledge that this index is also responsive to water presence, leading to the possibility that pixels identified as

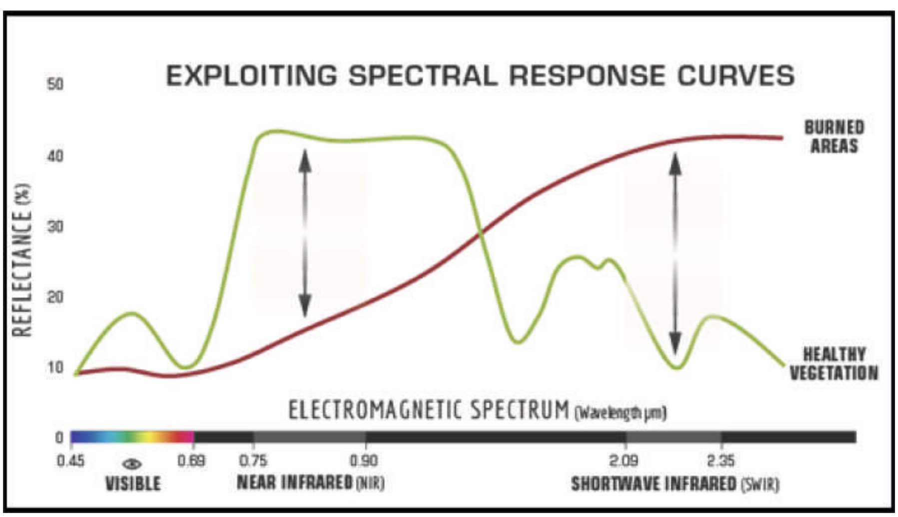

FIGURE 3 | Analyzing the spectral reactions of unharmed plant life and areas affected by fire. Source: US Forest Service.

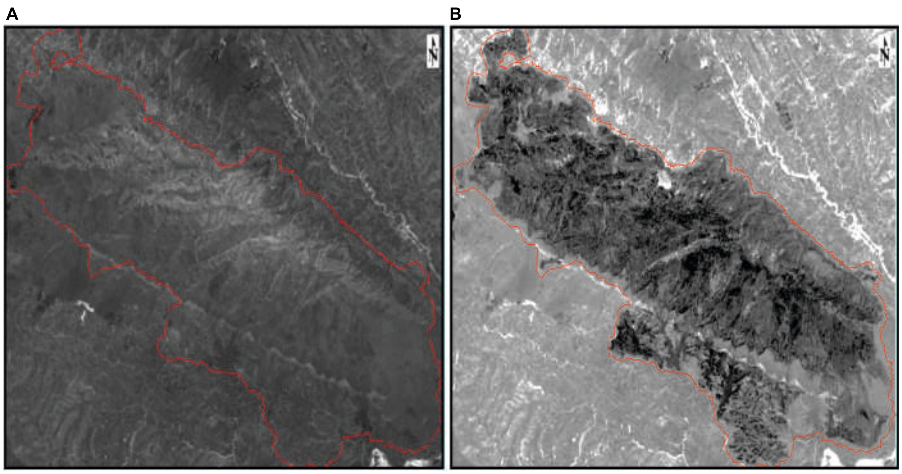

FIGURE 4 | (A) Application of the NBR index to the images after the fire. **(B)** Application of the NBR index to the images prior to the fire.

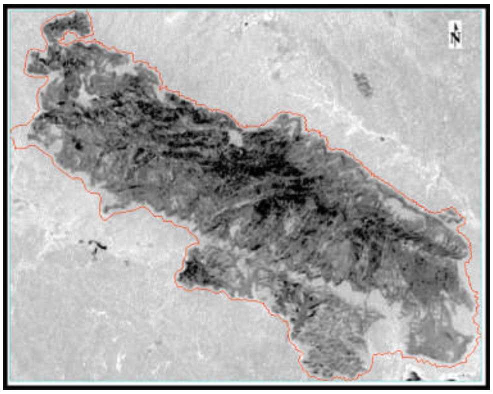

FIGURE 5 | Application of the dNBR index to the images.

"high intensity" may actually correspond to water bodies (15). To enhance precision, the process of cloud masking should be executed on the input imagery, generating a composite mask encompassing both water and cloud cover (13). For the assessment of fire severity, the computation of the difference between the pre-fire and post-fire NBR, denoted as delta NBR (dNBR or ΔNBR) (Formula 2), was conducted (14).

Assessing dNBR values individually in the field, whenever feasible, remains pivotal for achieving optimal outcomes, as these values can fluctuate based on distinct contextual factors (15). The United States Geological Survey (USGS) has introduced a classification table for the interpretation of fire severity (**Table 3**) (14). Normally, NBR and dNBR images are captured shortly after a fire to offer an initial appraisal of fire severity and to support on-site investigations (15). Subsequently, during the ensuing growing season, NBR datasets are frequently recalculated to appraise the endurance of vegetation and any deferred mortality (13). The datasets and maps pertaining to burn severity play a pivotal role in the formulation of post-fire recovery and rehabilitation strategies, the assessment of soil burn severity, and the anticipation of potential future repercussions stemming from occurrences such as floods, landslides, and soil erosion (14).

Nonetheless, as time passes and vegetation begins to reestablish itself following a fire, the efficacy of NBR diminishes (13), (**Figure 2**). Therefore, the applicability of the NBR ratio is heightened in regions where vegetation renewal is anticipated to be gradual, and its efficiency might decline in tropical areas characterized by high humidity and rapid growth rates (15). Considering the interval between the fire event and image capture is imperative for determining the optimal timing of assessment. Ideally, whenever feasible, the selection of pre- and post-fire images should closely correspond to the fire's occurrence date to mitigate adverse effects on dNBR values (3) (**Table 4**).

5. Discussion and findings

The results of applying the spectral index Between May 28 and June 2, 2020, a fire incident occurred at the Khaiz Anticline (10). The purpose of this investigation was twofold: first, to create a fire severity map for the area and second, to evaluate the effectiveness of the Delta Normal Burn Ratio (dNBR) index for economic management applications. The main objective of this project was to accurately delineate the zones affected by fire and optimize the efficient implementation of rehabilitation and reconstruction strategies. Spectral bands 8A (Red Edge 4) and 12 (SWIR 2) were used to execute the desired algorithm.

The pre-fire Normalized Burn Ratio (NBR) index results ranged from -0.39 to 0.16, while the post-fire NBR index results ranged from -0.28 to 0.46 (**Figure 3A**). The term "intensity" is qualitative and can be quantified in various ways. For instance, whether 0.5 represents "high intensity" or 0.66 does depends on the context. To ensure that fire intensity classification aligns with actual ground conditions, field evaluations should be conducted. The interpretation of ΔNBR values can vary based on their application, and in some cases, field evaluations are essential to obtain the most

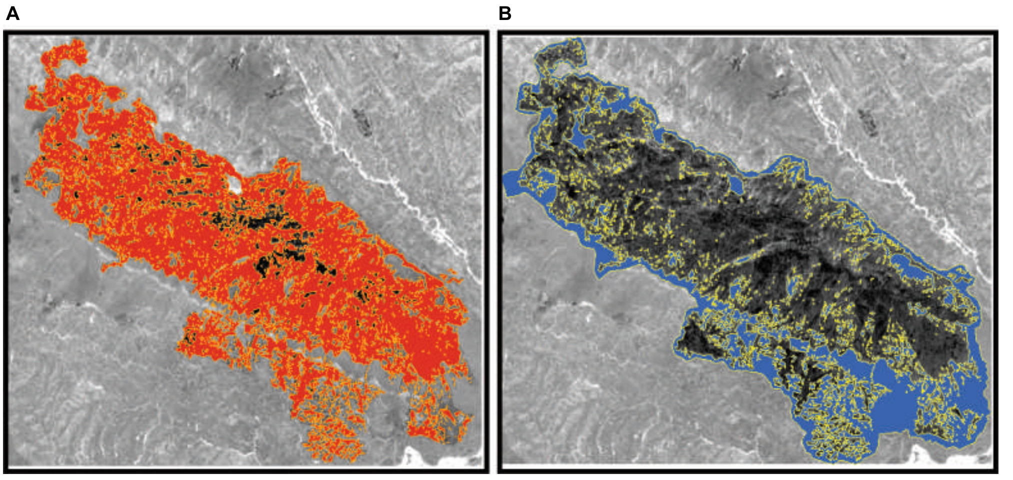

FIGURE 6 | (A) Burned area with low intensity. **(B)** Areas that have been spared from fire.

TABLE 5 | Area and percentage of fire intensity map.

Floor class	Quantitative results	area (square meter)	area (hectares)	Percent
Not burnt	0.096–0.099	15422840.59	1542.284	32.41
Down	0.100–0.269	29016749.25	2901.675	60.97
Average down	0.270–0.81	3149559.603	314.956	6.62
Total	–	47589149.44	4758.915	100.00

accurate results. The process of validating remote sensing data through field checks is known as validation.

Typically, NBR and ΔNBR images are captured shortly after a fire to provide an initial assessment of fire severity and aid in fieldwork (Figures 3B, 4).

Due to challenging weather conditions, long distances, difficult access, and impassable areas in the region, this study relied on automatically identifying fire severity and detecting the spatial pattern of fire severity using Sentinel-2A imagery. The values obtained with the desired index range from −0.096 to 0.81, with the maximum corresponding to the high-intensity class. The classification omits the lower portions of the upper middle class and the high-intensity class, resulting in an intensity map with three classes. According to the calculation method in this study, the size of the burned area is measured in hectares, and the distribution of burning intensity is as follows:

(1) The unburned area (Figure 5A) has values between 0.096 and 0.099, covering an area of 1542.284 hectares, representing 32.41% of the total area.
(2) The low-intensity area (Figure 5B) has values between 0.100 and 0.269, covering an area of 2901.675 hectares, representing 60.97% of the total area.
(3) The medium-intensity area (Figure 6) has values between 0.81 and 0.270, covering an area of 314.956 hectares, representing 6.62% of the total area (Table 5).

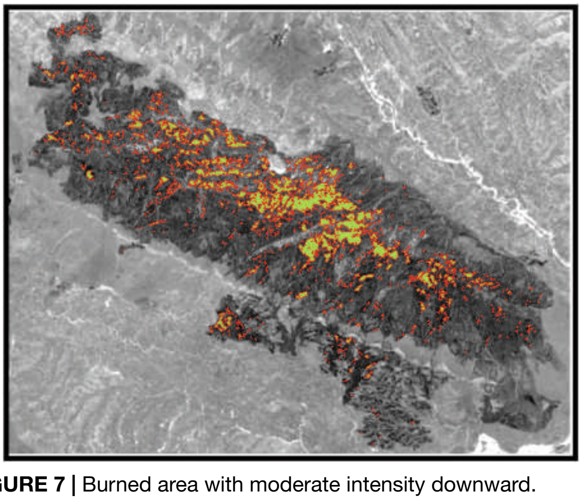

FIGURE 7 | Burned area with moderate intensity downward.

Certain areas within the fire zone remain unaffected by fire due to various reasons, such as rocky outcrops or vegetation-free areas. Selecting the most suitable spectral index for mapping burned areas can be challenging, especially if it has been used in multiple study sites. The results indicate that, for the Khaiz anticline, the spectral index used during the immediate post-fire assessment can be a valid and valuable tool for distinguishing burned from unburned areas. Figures 7 and 8 illustrate the range and spatial distribution of the fire resulting from the combination of DNBR and Land Surface Temperature (LST) layers with the RED band. The usage of different spectral indices for fire assessment may yield different values. However, variations in the set of separable indicators do not necessarily imply a lack of efficiency, as their performance is predominantly influenced by the local conditions of the region, including spatial and temporal factors, vegetation type, topography, area affected by fire, and vegetation density.

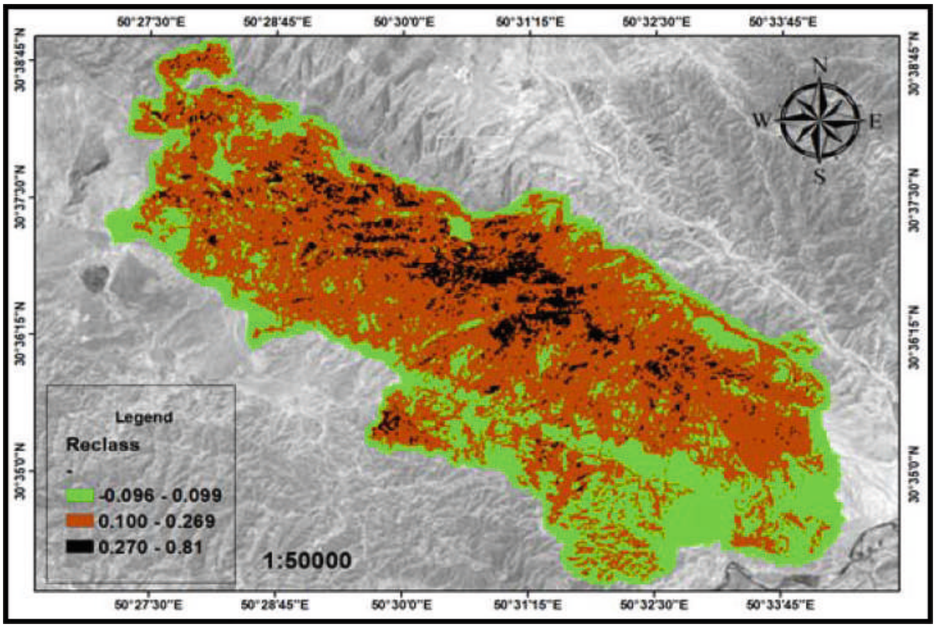

FIGURE 8 | Burn intensity map of the target area.

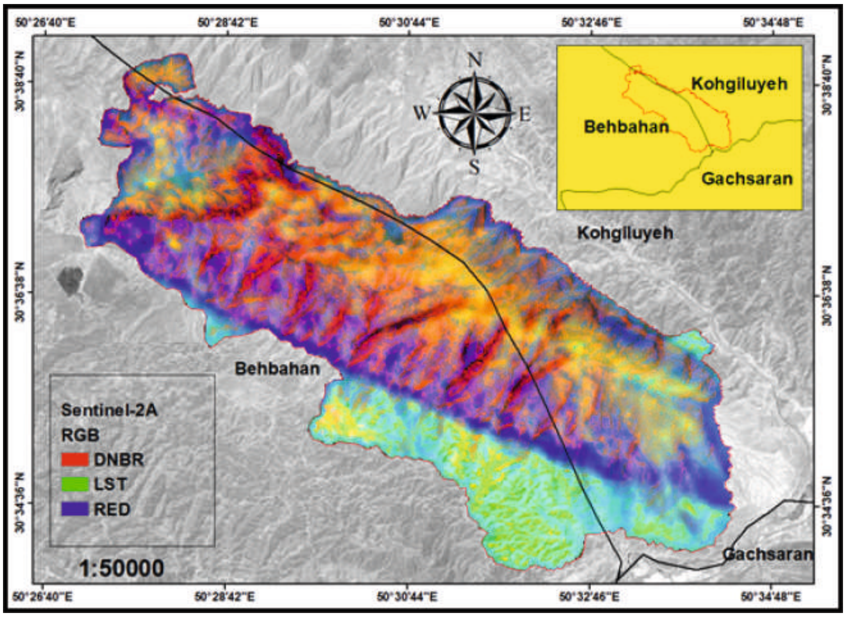

FIGURE 9 | Revealing the spatial spread of fire.

6. Conclusion

This study highlights the prominent role of remote sensing in fire mapping and detection, especially in the difficult terrain of the Khaiz anticline. This region is known for its complex mapping accuracy requirements and limited accessibility, and therefore benefits significantly from remote sensing, which increases fire identification accuracy and provides unbiased data based on the spatial evolution of the fire event. The study used a classification framework recommended by the United States Geological Survey that divides fire intensity into three different levels: not burned, burned at low intensity, and moderately damaged. The final results of the index evaluated had a range of −0.096 to 0.81.

From the results of the study, it appears that it is possible to delineate the zones affected by the fire. The area not burned covered 1542.3 hectares, which is about 32.4% of the total land area. The region with lowfire intensity covered 2904.7 hectares, which is 61% of the total land area. In addition, the moderate to low fire intensity section covered 315 hectares, or about 6.6% of the total area. Due to its limited extent, moderate-to-high-intensity and high-intensity burn categories were omitted from the analysis.

The maps and findings obtained from this study may be of considerable importance in formulating strategies for rejuvenating or restoring the impacted landscape. The study highlights the effectiveness of the dNBR spectral index in distinguishing areas that have been exposed to burning from those that have remained intact, in a mountainous environment characterized by warm climatic conditions and lush vegetation, especially in the immediate post-fire period.

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