A Machine Learning-Driven Framework for Comparative Multi-Algorithm Classification and Spatial Suitability Modelling of Saffron Cultivation in Pampore Karewas

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Abstract:

The study presents a comprehensive geospatial and machine learning-based framework for mapping, evaluating, and forecasting the spatial suitability of saffron cultivation in the Pampore Karewas of Jammu & Kashmir. Sentinel-2 imagery and ground-truth data were used to implement three supervised classifiers—Gradient Boosting, Random Forest, and Support Vector Machine (SVM)—to accurately detect saffron fields. Among these, Gradient Boosting demonstrated the highest classification performance, while Random Forest provided a balanced accuracy across classes. An Analytic Hierarchy Process (AHP)-based multi-criteria decision model, incorporating nine agro-environmental parameters, was developed to generate a saffron site suitability analysis for 2024. This was further integrated with classification outputs to delineate spatial priority zones for cultivation. To evaluate near-future viability, a climate-adjusted suitability model was constructed using ERA5 and CHIRPS datasets, incorporating saffron-specific temperature and rainfall thresholds through a rule-based penalty approach. Results indicate a projected 6.76% net reduction in highly suitable areas due to changing climatic conditions. While some traditional core production zones may face declining suitability, the analysis also highlights emerging potential in transitional zones, suggesting both challenges and new opportunities for adaptive saffron cultivation. The proposed methodology offers a scalable and replicable decision-support tool for climate-resilient agricultural planning and sustainable saffron farming under evolving environmental conditions.

1. Introduction

Saffron (Crocus sativus L.), one of the world's most valuable and climate-sensitive crops, is predominantly cultivated in the Pampore Karewas of Jammu & Kashmir, a region increasingly threatened by urbanization, land-use change, and climatic variability. This study proposes a robust geospatial and machine learning-based framework to delineate current cultivation zones, assess site suitability, and predict future viability of saffron farming under climate change. Using Sentinel-2 imagery and GPS-based ground truth data, three classification algorithms—Gradient Boosting, Random Forest, and Support Vector Machine—were implemented, with Random Forest achieving the highest accuracy. Suitability modeling was performed using the Analytic Hierarchy Process (AHP), incorporating nine agro-environmental factors. The classified output was integrated with the suitability model using weighted overlay analysis to generate a Priority Zone Map highlighting both cultivated and high-potential uncultivated areas. To evaluate future risks, a climate-adjusted suitability model applied rule-based penalties for temperature and precipitation anomalies using CHIRPS and ERA5-Land data. Similar approaches integrating AHP and GIS for saffron cultivation assessment have been successfully applied in Afghanistan (Wali et al., 2016), Iran (Maleki et al., 2017; Ehsan Falahat et al., 2019), and East Azerbaijan (Shokati et al., 2016), demonstrating the relevance of spatially explicit decision-making frameworks in agro-ecological planning. This study not only advances precision agriculture in Kashmir's saffron sector but also contributes a scalable model for managing climate-sensitive crops across other vulnerable agro-ecosystems.

2. Study Area

The The Pampore Karewas in the Kashmir Valley of Jammu & Kashmir (33°50′N–34°10′N, 74°30′E–75°10′E) are elevated lacustrine terraces formed through fluvio-lacustrine sedimentation, comprising fertile loamy to clayey soils rich in silt and organic matter (Jan, n.d.). Resting on Plio-Pleistocene sediments, their moderate elevation, gentle slopes, and favorable agro-climatic conditions make them highly suitable for saffron (*Crocus sativus* L.) cultivation (Maleki et al., 2017; Kumar et al., 2022). Known as the "Saffron Bowl of India," Pampore has experienced declining yields in recent decades due to erratic rainfall, urban encroachment, and soil degradation (Ayoub et al., 2024), highlighting the urgent need for precision agriculture and geospatial planning tools. Previous studies using multi-criteria evaluation and GIS-based approaches have successfully demonstrated how agro-environmental modeling can guide

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sustainable saffron cultivation under changing environmental conditions (Shokati et al., 2016; Ehsan Falahat et al., 2019; Wali et al., 2016). The environmental diversity and historical significance of Pampore make it an ideal region for testing machine learning-based classification and suitability models tailored to optimize land use, improve productivity, and safeguard saffron farming against climate-induced risks (Zamani et al., 2022; Sobhani, 2016).

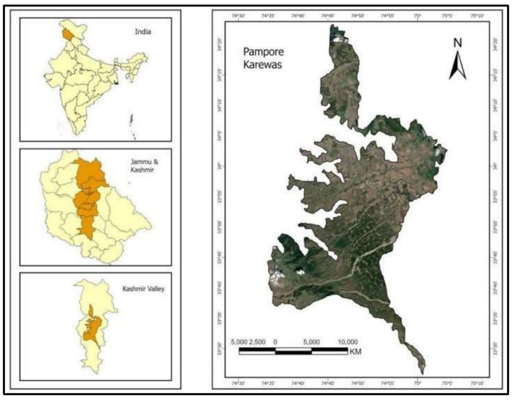

Figure 1. Map of the Study Area

3. Materials and Methods

The materials and methods section outlines the comprehensive framework adopted for mapping, assessing, and projecting saffron cultivation in the Pampore Karewas of Jammu & Kashmir. It integrates remote sensing, machine learning classification, multi-criteria decision analysis, and climate sensitivity modeling to derive spatially explicit and actionable insights.

3.1 Data used

The data employed in this study is classified into three main categories: raster data, ancillary data, and secondary ground-truth data. The raster datasets included high-resolution Sentinel-2 imagery (10 m) from the Copernicus Sentinel Hub, SRTM Digital Elevation Model (30 m) from USGS Earth Explorer, and a range of climate and environmental variables sourced from Google Earth Engine. These included ERA5-Land hourly rainfall and temperature datasets (9 km resolution) for 2024 and 2019–2020, CHIRPS daily rainfall data (5.5 km), and OpenLandMap soil organic carbon (250 m). Ancillary vector data consisted of the Pampore Karewas boundary, derived from the thesis “Digital Mapping of Saffron Growing Soils of District Pulwama” (Jan, K.), and the India road network acquired from OpenStreetMap (GeoFabrik). The secondary ground-truth data, also extracted from Jan's thesis, included 60 georeferenced soil sample points collected across 20 locations in the Pampore Karewas during autumn 2022 using a random sampling approach. Each site contributed three samples taken at 0–30 cm soil depth, with corresponding GPS coordinates and elevation values. These locations spanned key saffron-producing villages such as Meej, Patalbagh, Dussu, Letpora, Chandhara, Wuyan, Krechoo, Konibal, Munpur, Androosa, Ladhoo, Sambora, Balhuma, Baras, Hatiwara, Koil, Awantipora, and Krew. This comprehensive and spatially distributed dataset was crucial for training and validating the machine learning classifiers, thereby enhancing the robustness and spatial accuracy of the classification and suitability modeling.

3.2 Workflow

The methodological workflow of this study follows a structured, multi-stage geospatial and machine learning-based framework to assess, map, and project saffron cultivation potential in the Pampore Karewas of Jammu & Kashmir. Initially, high-resolution Sentinel-2 imagery and ancillary environmental raster datasets (elevation, slope, aspect, NDVI, LULC, rainfall, temperature, soil carbon, and distance from roads) were acquired, while 60 georeferenced ground-truth points were derived from a prior study (Digital Mapping of Saffron Growing Soils of District Pulwama by Jan, K.). These datasets provided the foundation for subsequent classification and suitability modeling.

3.2.1 Machine Learning Classification - Gradient Boosting, Random Forest, and SVM: A supervised binary classification approach was implemented using Gradient Boosting, Random Forest, and Support Vector Machine (SVM) algorithms, which have been widely adopted in recent saffron cultivation suitability and land classification studies (Shokati & Feizizadeh, 2019; Kumar et al., 2022). The labeled ground-truth data was split into 70% training and 30% testing sets, and features were standardized to ensure uniform scale. The classifiers were trained to predict saffron (1) and non-saffron (0) pixels, and their performance was evaluated using key metrics including accuracy, precision, recall, F1-score, and ROC-AUC—a standard evaluation framework in spatial classification modeling (Maleki et al., 2017; Ehsan Falahat et al., 2019). Among the three, Random Forest demonstrated the highest classification accuracy and generalizability, consistent with findings from earlier agro-ecological classification efforts involving complex spatial data (Wali et al., 2016; Binesh et al., 2020).

3.2.2 AHP and Weighted Overlay for Site Suitability Mapping: Agro-environmental raster parameters were reclassified into four suitability categories (Very Low to Very High), and the Analytic Hierarchy Process (AHP) was used to assign weights based on expert judgment and established saffron-growing requirements (Wali et al., 2016; Ehsan Falahat et al., 2019; Sobhani, 2016). The weighted layers were then integrated using GIS-based Weighted Overlay Analysis to generate a Site Suitability Map for 2024, identifying potential zones for saffron expansion. This approach follows a well-documented multi-criteria evaluation framework used in saffron cultivation modeling (Maleki et al., 2017; Shokati et al., 2016; Zamani et al., 2022), providing a comprehensive spatial decision-making methodology for assessing agro-ecological potential.

3.2.3 Integrated Priority Zone Mapping: To assess ground-truth alignment with modeled suitability, classified saffron rasters were overlaid with the suitability output to perform pixel-wise distribution analysis—an approach consistent with spatial accuracy assessments used in saffron modeling studies (Shokati et al., 2016; Maleki et al., 2017). A Pearson correlation along with logistic regression and sigmoid curve fitting was conducted to statistically evaluate the spatial agreement between classified saffron patches and modeled suitability scores, aligning with methods adopted in previous spatial evaluation frameworks

(Ehsan Falahat et al., 2019; Shokati & Feizizadeh, 2019). An integrated Priority Zone Map was then generated by combining outputs from all three classifiers (e.g., Random Forest, Gradient Boosting, and SVM) with the suitability map. This enabled visualization of both existing cultivation zones and ecologically suitable but currently uncultivated areas, a strategy also echoed in studies introducing saffron to new regions through ecological modeling (Kumar et al., 2022; Wali et al., 2016).

3.2.4 Climate-Adjusted Suitability Modeling: To incorporate climate vulnerability into the saffron cultivation suitability assessment, ERA5 and CHIRPS datasets for 2019–2020 were used to compute baseline mean temperature and rainfall. A rule-based penalty approach—similar to climate response modeling in earlier saffron suitability studies (Ayoub et al., 2024; Kumar et al., 2022)—was applied to adjust the 2024 suitability scores. Specifically, a 5% suitability reduction was implemented per °C increase above 30°C, and a 3% reduction was applied for every additional 100 mm rainfall during the flowering period, aligning with known physiological stress responses of Crocus sativus L. (Binesh et al., 2020; Rajabi et al., 2016). These coefficients were incorporated to refine the model, following ecological modeling strategies developed in similar agro-ecological zoning efforts (Sobhani, 2016; Zamani et al., 2022). The resulting Climate-Adjusted Suitability Map presents a forward-looking perspective on the resilience and vulnerability of saffron cultivation zones amid anticipated temperature and precipitation shifts, advancing earlier GIS and AHP-based approaches (Ehsan Falahat et al., 2019; Wali et al., 2016; Shokati & Feizizadeh, 2019).

Collectively, this methodology leverages remote sensing, machine learning, multi-criteria decision analysis, and climate risk modeling to deliver a comprehensive, scalable, and policy-relevant framework for sustainable saffron cultivation planning in fragile agro-ecosystems.

4. Results and Discussions

The classification framework began with Python-based machine learning algorithms—Gradient Boosting, Random Forest, and Support Vector Machine (SVM)—to identify saffron and non-saffron areas across the Pampore Karewas, Pulwama district. A total of 60 ground-truth soil sample points, sourced from Jan (n.d.), were used for training and validation.

4.1 Binary Classification Results of Saffron Cultivation Using Machine Learning Models

As demonstrated in Figure 2, the results highlight a trade-off among models: Gradient Boosting is more inclusive, SVM more restrictive, and Random Forest strikes a middle ground in estimating saffron coverage.

The Gradient Boosting classifier achieved the highest overall accuracy (79.17%) and recall for saffron (84.6%), mapping saffron patches mainly across southern and southwestern regions such as Pampore, Khrew, and Chandhara in Figure 2(a). It estimated 156,112.05 ha of saffron area, indicating a broader inclusion of marginal patches.

In Figure 2(b), the Random Forest classifier showed balanced performance with an overall accuracy of 75% and saffron F1-score of 0.79, estimating 131,606.66 ha of saffron. Its predictions were concentrated around central Pampore and neighboring areas, reflecting a stable and generalized classification output.

In contrast, the Figure 2(c) shows that the SVM classifier was more conservative, producing the lowest overall accuracy (66.67%) but highest recall (92.31%) for saffron. It estimated 124,178.08 ha as saffron, underclassifying non-saffron zones (producer's accuracy: 36.36%), suggesting overprediction.

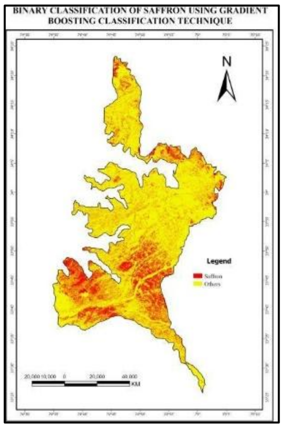

Figure 2(a)

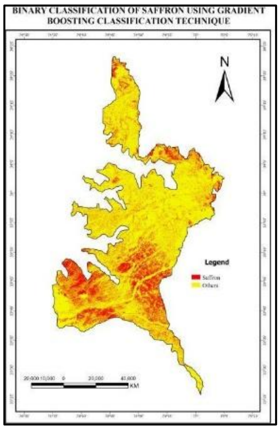

Figure 2(b)

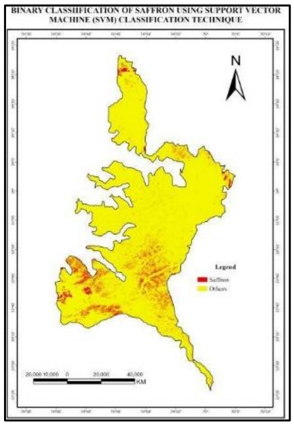

Figure 2(c)

Figure 2(a-c). Results of Binary Classification performed using the ML classifiers

4.1.2 Model Evaluation Using ROC-AUC Metrics: The Receiver Operating Characteristic (ROC) curves and corresponding Area Under the Curve (AUC) values were used to evaluate the classification performance of the machine learning models applied for saffron mapping. In Figure 3(a), Gradient Boosting demonstrated the highest AUC (0.85), indicating strong discriminatory power, followed by Random Forest in Figure 3(b), with an AUC of 0.83, reflecting robust spatial classification accuracy. In Figure 3(c), Support Vector Machine (SVM) achieved a lower AUC of 0.79, suggesting moderate performance and a conservative classification approach. Overall, ensemble-based models like Gradient Boosting and Random Forest outperformed SVM in effectively capturing the complex spatial variability of saffron cultivation zones in the Pampore Karewas.

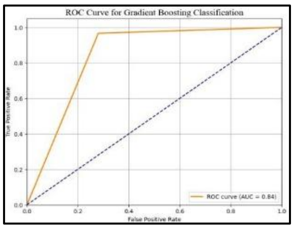

Figure 3(a)

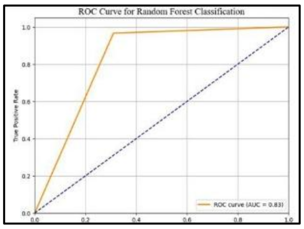

Figure 3(b)

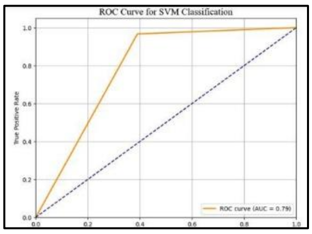

Figure 3(c)

Figure 3(a-c). Results of ROC and AUC of the classifiers performed

4.2 Multi-Criteria Site Suitability Analysis for Saffron Cultivation Using AHP

In this study, a GIS-based multi-criteria decision-making approach was used to evaluate the suitability of saffron cultivation across the Pampore Karewas. The analysis incorporated nine key agro-environmental parameters: Normalized Difference Vegetation Index (NDVI), elevation, slope, aspect, land use/land cover (LULC), rainfall, temperature, soil carbon content, and distance from roads—each selected based on their agronomic importance to saffron growth and viability.

To quantify the influence of each parameter, the Analytical Hierarchy Process (AHP) was applied. A pairwise comparison matrix using Saaty's 1–9 scale was developed, followed by normalization and computation of priority weights. NDVI and LULC were found to be the most influential (0.20 each), followed by elevation (0.13) and soil carbon content (0.12), while aspect and distance from roads were the least influential. The consistency ratio (CR = 0.0026) was well below the acceptable threshold of 0.10, confirming the logical coherence and robustness of the weighting process.

Table 1. Table showing parameters used for AHP and consecutive weights of each

Criteria	AHP Weight
Elevation	0.13
Slope	0.08
Aspect	0.04
LULC	0.2
Rainfall	0.08
Temperature	0.08
Soil_carbon	0.12
Distance_roads	0.07
NDVI	0.2

The final weights were used in a weighted overlay analysis in a GIS environment as shown in Figure 4, to generate the saffron suitability map, classifying the region into four zones: very low, low, high, and very high suitability. Spatial interpretation showed that highly suitable zones were characterized by moderate NDVI, low to mid elevation, gentle slopes, favorable aspects (NE–SE), agricultural land cover, moderate rainfall, suitable temperature ranges, fertile soils, and accessibility via road networks. Conversely, areas with steep slopes, poor accessibility, or extreme climatic conditions were mapped as less suitable.

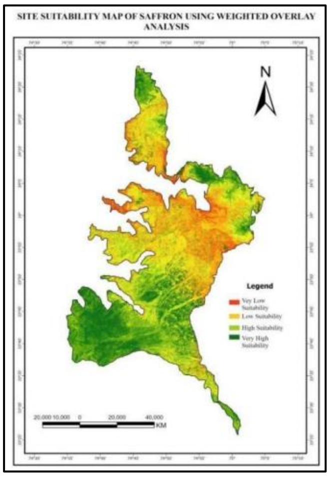

Figure 4. Map showing the Site Suitability Analysis performed

The suitability analysis revealed that the majority of the Pampore Karewas region is favorable for saffron cultivation, with approximately 180,986.24 hectares categorized as "Moderate" suitability and 180,264.41 hectares as "High" suitability. Together, these two classes account for nearly 99% of the total area, underscoring the region's broad agro-environmental potential. In contrast, areas classified as "Low" (5,327.00 ha) and "Very Low" (186.63 ha) suitability represent only a small fraction of the landscape, typically characterized by limitations such as steep slopes, low soil fertility, or poor accessibility.

4.3 Model Validation through Pixel-Level Evaluation and Logistic Regression Analysis

To assess spatial precision, pixel-level classification using Sentinel-2 imagery and ground-truth data was conducted through three machine learning models: Gradient Boosting, Random Forest, and Support Vector Machine (SVM) as shown in Figure 5. Overlay analysis with the suitability zones revealed strong agreement for Gradient Boosting and Random Forest, where 83.0% and 85.0% of saffron pixels, respectively, were concentrated in "High" suitability areas, while minimal presence was noted in the "Very Low" category (8.0% and 7.0%). This alignment validates the robustness of both classification algorithms and the underlying suitability framework.

In comparison, SVM exhibited weaker correspondence with the suitability zones. Despite an overall trend of increased saffron presence in higher suitability classes, the model misclassified 21.0% of saffron pixels in "Very Low" zones and showed only 53.0% in "High" suitability, indicating reduced sensitivity in BJdistinguishing complex spatial patterns. These inconsistencies may be attributed to SVM's limitations in handling overlapping class boundaries and non-linear feature distributions in remote sensing data.

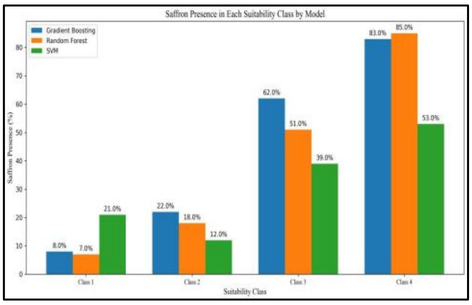

Figure 5. Barplot showing Saffron presence by pixel in each Suitability Zone

To validate the saffron suitability model, logistic regression was employed using ground-truth classification data to assess the relationship between continuous suitability scores and actual saffron presence. In Figure 6, the Gradient Boosting model demonstrated the strongest predictive performance, with a high Pearson correlation of 0.895 and a well-defined sigmoid curve indicating a sharp increase in saffron probability with higher suitability values. It achieved a balanced precision, recall, and F1-score of approximately 0.80 and an overall accuracy of 79%. The Random Forest model followed with a moderate correlation of 0.631 and 75% accuracy, characterized by strong recall (0.85) for saffron but a more gradual probability trend. Conversely, the SVM model showed weaker alignment, with a correlation of 0.628, highly skewed recall (0.92 for saffron vs. 0.36 for non-saffron), and a lower accuracy of 67%, suggesting poor class balance and reduced generalizability in Figure 6(c). These results confirm Gradient Boosting as the most reliable model for mapping spatial saffron suitability in the heterogeneous landscapes of the Pampore Karewas, followed by Random Forest, while SVM proved less robust

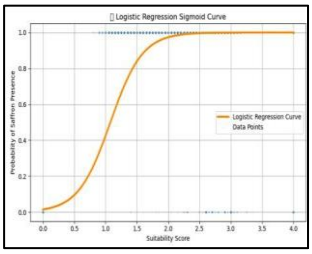

Figure 6(a)

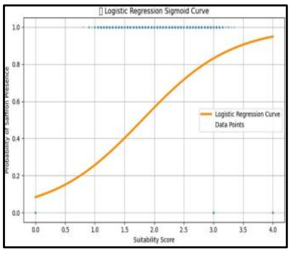

Figure 6(b)

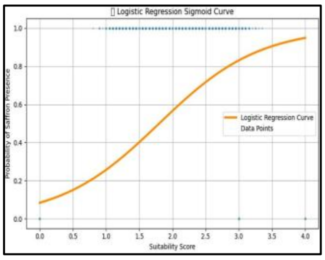

Figure 6(c)

Figure 6(a-c). Sigmoid Curve showing Logistic Regression of the classifiers performed

4.4 Integrated Spatial Prioritization Mapping for Saffron Cultivation

This study employs an integrated geospatial framework to delineate Priority Zones for saffron cultivation in the Pampore Karewas by combining machine learning outputs, environmental suitability scores, and climate-adaptive planning. A weighted overlay analysis was performed using results from Gradient Boosting (weight: 3), Random Forest (2), SVM (1), and AHP-based site suitability (1.5) to generate a composite Priority Zone Map, classifying the area into Very High, High, Low, and Very Low priority classes. Very High Priority zones—primarily in Lethapora, Konibal, Chandhara, and Khrew—cover 32,445 ha and exhibit strong classifier consensus and optimal environmental conditions. High Priority zones (120,640 ha) extend into Samboora, Ladhoo, and Barsoo with moderate suitability and agreement from at least two models. Conversely, Low and Very Low Priority areas (199,520 ha), including Wuyan, Androosa, and Shar Shali, are constrained by poor terrain and low model consensus. This integrated mapping supports targeted investment and sustainable planning for saffron cultivation under evolving climatic conditions.

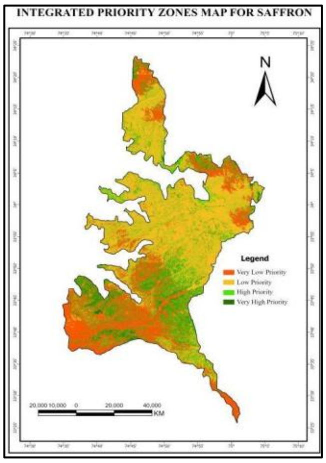

Figure 7. Map showing the Integrated Priority Zone mapping performed

4.5 Climate-Integrated Projection of Saffron Suitability in Pampore Karewas

This section models the future suitability of saffron cultivation in the Pampore Karewas by incorporating climate sensitivity into the 2024 baseline suitability framework. The baseline map, developed using geospatial analysis of soil characteristics, topography, and land use/land cover, was adjusted based on recent climatic data from ERA5-Land (temperature) and CHIRPS (precipitation) for the years 2019 and 2020. Saffron-specific climate thresholds were used to simulate future impacts—namely, a 5% reduction in suitability per °C increase beyond 30°C and a 3% reduction per additional 100 mm of rainfall during the flowering stage.

Analysis of 2019–2020 revealed favorable growing conditions: maximum summer temperatures remained below 20°C, and flowering-season rainfall was consistently low (<10 mm), avoiding any climate-induced reductions in suitability. However, slight increases in pre-flowering rainfall in 2020 suggest emerging trends that could influence future cultivation if intensified.

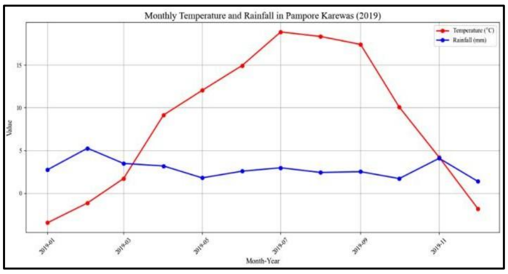

Figure 8(a)

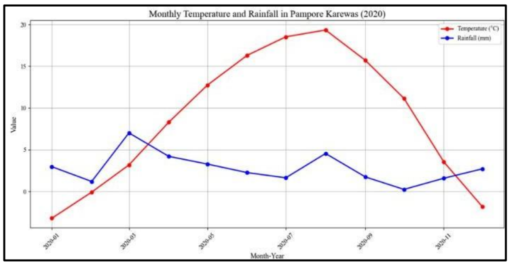

Figure 8(b)

Figure 8(a-b). Line Graphs showing distribution of temperature amd rainfall 2019-2020

Climate-adjusted projections for future conditions anticipate a ~2°C increase in summer temperatures (peaking near 21°C) and a potential rise in rainfall during October–November. While temperature remains below saffron’s stress threshold, a projected 100 mm increase in precipitation could result in a 3% decrease in suitability due to excess soil moisture, especially during the flowering phase.

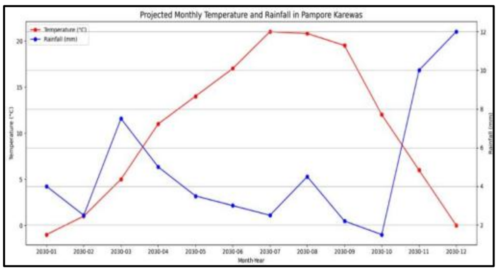

Figure 9. Line graph showing projected distribution of temperature and rainfall considering climate adjustments

Spatial analysis shows that Very High and High Suitability zones are likely to persist in the core Pampore region and parts of eastern Khrew, supported by favorable elevation, soil texture, and drainage. However, Moderate zones near Barsoo and Khonmoh show sensitivity to climatic variation, and previously marginal areas like Sambora, Androosa, and the northwestern Karewa fringes further decline in suitability. Notably, some minor improvements in Low and Very Low Suitability areassuggest potential localized benefits from improved moisture conditions or land stabilization.

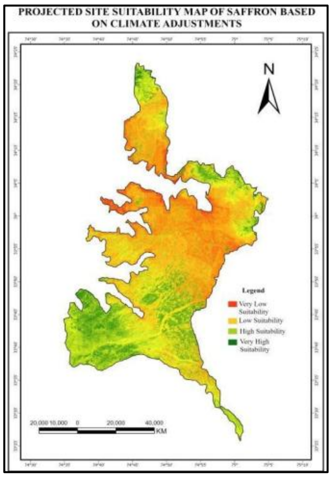

Figure 10. Map showing the Projected Site Suitability Analysis considering the climate adjustments

Quantitatively, the area under Very High Suitability is projected to shrink from 180,264 ha in 2024 to 160,200 ha in near future—a net loss of 20,064 ha (11.1%). High Suitability zones decrease by 2.4%, while Very Low and Low zones expand by 19.6% and 9.9%, respectively, reflecting growing agro-climatic stress and reinforcing the need for climate-adaptive strategies.

Table 2: Table showing change in area considering climate adjusments

Class	Area (ha) 2024	Area (ha) Future	Change (ha)	Change (%)
Very Low	186.63	223.20	36.57	19.59%
Low	5327.00	5859.00	532.00	9.99%
High	180986.24	176640.00	4346.24	2.40%
Very High	180264.41	160200.00	20064.41	11.13%

These findings indicate that while the Pampore Karewas will continue to support saffron cultivation in core zones, the region as a whole is projected to experience a net loss of 6.76% in overall suitability considering the climayic sensitivity. This decline is primarily driven by rising summer temperatures and increased rainfall during the flowering stage, which may induce soil moisture stress. Peripheral areas, particularly those already marginal in 2024, show further degradation in suitability, underscoring the growing vulnerability of saffron cultivation to agro-climatic variability. To ensure long-term sustainability, targeted interventions—such as improved drainage infrastructure, adaptive water management, and climate-resilient land-use zoning—are essential to mitigate projected losses and maintain the viability of saffron agriculture under future climate scenarios.

The climate-adjusted suitability analysis for modelling the near future reveals a dual narrative: while the central Pampore core continues to act as a resilient stronghold for saffron cultivation, marginal and transitional zones are increasingly vulnerable to climate-induced degradation.

5. Conclusion

This study presents a robust, multi-algorithmic geospatial framework for classifying, assessing, and prioritizing saffron cultivation in the Pampore Karewas by integrating machine learning classification, GIS-based suitability modeling, and climate sensitivity analysis. Among the classifiers, Gradient Boosting proved to be the most reliable for capturing complex spatial patterns, while Random Forest offered a balanced performance, and SVM exhibited limitations in differentiating marginal classes. The AHP-derived suitability model underscored the critical roles of NDVI, LULC, and elevation in determining saffron viability, showing strong alignment with classification results. By merging classifier predictions with environmental parameters, the Priority Zone Map facilitated targeted zoning to optimize resource allocation and agricultural planning. Climate-adjusted suitability projections revealed both resilience and vulnerability across the landscape—core zones such as Pampore, eastern Khrew, and Chandhara remained favorable, while marginal areas like Sambora, Androosa, and Barsoo showed a notable decline in suitability. Overall, the High and Very High Suitability zones contracted by approximately 6.76%, equating to a loss of around 25,170 hectares of prime cultivation area, primarily due to rising summer temperatures and erratic rainfall during flowering periods. Nonetheless, minor improvements in select low-suitability zones highlight localized adaptation potential driven by favorable microclimates or improved soil-moisture dynamics. This comprehensive framework provides a scalable and transferable methodology for climate-resilient crop planning and reinforces the importance of evidence-based policy and adaptive management to secure the future of saffron cultivation in Kashmir and other vulnerable agro-ecological systems.

6. Acknowledgement

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