

DEEP LEARNING-BASED ENHANCEMENT OF SENTINEL-2 IMAGES FOR FIELD-SCALE EVAPOTRANSPIRATION ESTIMATION

AMÉLIORATION DES IMAGES SENTINEL-2 PAR APPRENTISSAGE PROFOND POUR L'ESTIMATION DE L'ÉVAPOTRANSPIRATION À L'ÉCHELLE DE LA PARCELLE

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ABSTRACT

Accurate estimation of actual evapotranspiration (ET_a) at the field scale is a fundamental requirement for optimal irrigation planning and sustainable water resource management, especially in regions with small and fragmented agricultural lands. The limited spatial resolution of available satellite images often leads to the mixed pixel problem, in which each pixel represents a combination of agricultural and non-agricultural land uses. This issue significantly reduces the accuracy of remotely sensed vegetation indices, estimation of leaf area index (LAI), and consequently ET_a . The present study investigates the effect of improving satellite images spatial resolution on resolving mixed pixel problem and enhancing the accuracy of LAI and ET_a estimation in small fields. The required data were obtained from previous studies conducted in rice experimental fields located at the Rice Research Institute of Iran (RRII) in Gilan Province, north of Iran. The region is characterized by a humid to very humid climate, with a mean annual precipitation of approximately 1500 mm and a mean annual air temperature of about 16.7 °C, suitable for paddy rice cultivation.

The field data used in this research comprised two distinct experimental periods. During the 2017 cropping season, observations were obtained from four rice plots equipped with lysimeters, providing simultaneous in situ measurements of LAI and ET_a . In the second dataset, LAI measurements from another experiment conducted during the 2018 and 2019 cropping seasons were utilized. Data of years 2018 and 2019 were used for model development, while the 2017 data were employed for validation. Multispectral images from Sentinel-2, Landsat 7, and Landsat 8 were used to extract vegetation indices, including NDVI and SAVI. A deep learning-based super-resolution model was applied to Sentinel-2 images to enhance the spatial resolution from 10 m to 1 m while keeping spectral integrity. The enhanced images showed a very high correlation between reconstructed and original NDVI values ($R = 0.9979$), indicating a substantial improvement in spatial detail without spectral distortion. LAI was estimated using regression models based on NDVI and SAVI, and the results demonstrated that NDVI provided more reliable LAI estimates than SAVI, with RMSE values ranging from 0.51 to 0.61 and MAE values between 0.38 and 0.49. Based on NDVI-derived LAI, ET_a was subsequently estimated using a crop coefficient-based approach (K_c), in which K_c values derived from LAI were combined with reference evapotranspiration. This approach showed close agreement with lysimetric observations, with RMSE values ranging between 0.40 and 0.58-mm day⁻¹ and normalized RMSE values of 7 to 11%. Estimated cumulative evapotranspiration during the rice growing season of four independent plots ranged from 397 to 441 mm, showing good agreement with lysimetric measurements. Overall, the results demonstrate that increasing the spatial resolution of satellite images by this novel approach significantly improves LAI and ET_a estimation in small and fragmented agricultural fields by reducing mixed pixel effects. The proposed framework provides a practical and transferable solution for improving field-scale irrigation water management, particularly in regions where agricultural plot sizes are smaller than the native spatial resolution of commonly used satellite sensors.

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Keywords: Actual evapotranspiration; Sentinel-2; Leaf area index (LAI); Deep learning.

RÉSUMÉ

L'estimation précise de l'évapotranspiration réelle (ET_a) à l'échelle de la parcelle constitue une condition fondamentale pour une planification optimale de l'irrigation et une gestion durable des ressources en eau, en particulier dans les régions où les terres agricoles sont petites et morcelées. La résolution spatiale limitée des images satellitaires disponibles entraîne souvent le problème des pixels mixtes, dans lequel chaque pixel représente une combinaison d'occupations agricoles et non agricoles du sol. Ce problème réduit sensiblement la précision des indices de végétation issus de la télédétection, de l'estimation de l'indice foliaire (LAI) et, par conséquent, de l' ET_a . La présente étude examine l'effet de l'amélioration de la résolution spatiale des images satellitaires sur l'atténuation du problème des pixels mixtes et sur l'amélioration de la précision de l'estimation du LAI et de l' ET_a dans les petites parcelles. Les données requises provenaient d'études antérieures menées dans des rizières expérimentales situées à l'Institut iranien de recherche sur le riz (IRRI), dans la province de Guilan, au nord de l'Iran. La région se caractérise par un climat humide à très humide, avec des précipitations annuelles moyennes d'environ 1 500 mm et une température annuelle moyenne de l'air d'environ 16,7 °C, propice à la riziculture inondée.

Les données de terrain utilisées dans cette recherche couvraient deux périodes expérimentales distinctes. Pendant la campagne agricole de 2017, les observations ont été recueillies dans quatre parcelles de riz équipées de lysimètres, fournissant des mesures in situ simultanées du LAI et de l' ET_a . Le second jeu de données utilisait des mesures du LAI issues d'une autre expérience menée pendant les campagnes agricoles de 2018 et 2019. Les données de 2018 et 2019 ont servi à élaborer le modèle, tandis que celles de 2017 ont été utilisées pour sa validation. Des images multispectrales de Sentinel-2, Landsat 7 et Landsat 8 ont été utilisées pour extraire les indices de végétation, notamment le NDVI et le SAVI. Un modèle de super-résolution fondé sur l'apprentissage profond a été appliqué aux images Sentinel-2 afin d'en améliorer la résolution spatiale de 10 m à 1 m tout en préservant l'intégrité spectrale. Les images améliorées ont présenté une corrélation très élevée entre les valeurs reconstruites et originales du NDVI ($R = 0,9979$), ce qui indique un enrichissement considérable des détails spatiaux sans distorsion spectrale. Le LAI a été estimé au moyen de modèles de régression fondés sur le NDVI et le SAVI ; les résultats ont montré que le NDVI fournissait des estimations du LAI plus fiables que le SAVI, avec des valeurs de RMSE comprises entre 0,51 et 0,61 et des valeurs de MAE comprises entre 0,38 et 0,49. À partir du LAI dérivé du NDVI, l' ET_a a ensuite été estimée selon une approche fondée sur le coefficient cultural (K_c), dans laquelle les valeurs de K_c dérivées du LAI ont été combinées à l'évapotranspiration de référence. Cette approche a montré une étroite concordance avec les observations lysimétriques, avec des valeurs de RMSE comprises entre 0,40 et 0,58 mm jour⁻¹ et des valeurs de RMSE normalisée de 7 à 11 %. L'évapotranspiration cumulée estimée pendant la saison de croissance du riz dans les quatre parcelles indépendantes variait de 397 à 441 mm, en bonne concordance avec les mesures lysimétriques. Dans l'ensemble, les résultats montrent que l'augmentation de la résolution spatiale des images satellitaires au moyen de cette nouvelle approche améliore sensiblement l'estimation du LAI et de l' ET_a dans les petites parcelles agricoles morcelées en réduisant les effets des pixels mixtes. Le cadre proposé offre une solution pratique et transférable pour améliorer la gestion de l'eau d'irrigation à l'échelle de la parcelle, en particulier dans les régions où la taille des parcelles agricoles est inférieure à la résolution spatiale native des capteurs satellitaires couramment utilisés.

Mots clés : Evapotranspiration réelle; Sentinel-2; Indice de surface foliaire (LAI); Apprentissage profond.

1. Introduction

Iran's location within the arid and semi-arid belt of the world, with an annual rainfall of only about one-third of the global average, makes the country inherently vulnerable to water scarcity and underscores the urgent need for efficient water-resources management (Heidari & Saraei-Tabrizi, 2015). In this context, accurate estimation of actual evapotranspiration is vital for optimizing irrigation.

However, direct measurement methods such as lysimeters, despite their high accuracy, are costly, labor-intensive, time-consuming, and produce point-scale data that cannot be easily scaled to large agricultural regions. These limitations emphasize the need for alternative and more efficient spatial approaches to monitor water use (Pandy et al., 2023).

In this regard, LAI as an indicator representing canopy development and leaf area, leads to higher actual evapotranspiration through its association with an increased crop coefficient (K_c), making it a useful tool for estimating ET across large spatial scales (Jia & Wang, 2021). LAI can be estimated from vegetation indices derived from multispectral satellite data. The Normalized Difference Vegetation Index (NDVI) (Rouse et al., 1973) and the Soil-Adjusted Vegetation Index (SAVI) (Huete, 1988) are among the most widely used indices because they are sensitive to green vegetation cover and partially reduce the influence of soil background. The strong empirical relationship between these indices and LAI has made NDVI and SAVI practical tools for describing canopy structure and transpiration in studies of actual evapotranspiration. Effective use of these indices, however, requires spatial data with suitable spectral characteristics and sufficient spatial resolution to distinguish small agricultural plots. In this regard, the Sentinel-2 mission within the Copernicus program provides multispectral images with 13 spectral bands and spatial resolutions ranging from 10 to 60 m, specifically designed for land and vegetation monitoring (Drusch et al., 2012).

The red and near-infrared bands with 10 m resolution enable the production of NDVI and SAVI maps over agricultural areas. However, in many irrigated regions in Iran—particularly small and fragmented paddy fields—this spatial resolution leads to mixed pixels that contain a combination of vegetation, soil, and water. Such mixed pixels reduce the accuracy of vegetation indices, introduce bias into LAI estimation, and consequently increase the uncertainty of ETa estimates. To alleviate this problem, deep learning-based super-resolution methods can be used to enhance spatial details while preserving spectral characteristics. In this study, the S2DR3 super-resolution model is employed, which builds upon the ESRGAN architecture and Residual-in-Residual Dense Blocks (RRDB) introduced by Wang et al. (2018).

S2DR3 has been applied to increase the spatial resolution of Sentinel-2 data to approximately 1 m in agricultural remote sensing applications (S2DR3, 2023). The super-resolved images, together with the original Sentinel-2 data, are used to derive NDVI and SAVI, estimate LAI, and compute ETa at both the original and the enhanced spatial resolutions.

2. Materials and Methods

2.1 Study area and experimental setup

The study was conducted in Guilan province, located in northern Iran, which is the country's primary rice-producing region (Figure 1). The experimental site is situated in the research fields of the Rice Research Institute of Iran in Rasht city. The region experiences a highly humid climate, characterized by an average annual precipitation of 1478 mm and a mean annual temperature of 16.7°C. For the 2017 growing season, the required field data were provided from a study conducted on four distinct paddy plots cultivated with the improved Hashemi rice cultivar at 37°12' N latitude and 49°38' E longitude.

The study area is located at the Rice Research Institute of Iran in Rasht (37° 12' N, 49° 38' E). To validate the remote sensing models developed in this research, we utilized accurate in-situ data extracted from the field experiments conducted by Pandi et al. (2019) on four paddy plots cultivated with the Hashemi rice cultivar. The reference dataset from their study included daily actual evapotranspiration measurements, collected via lysimeters (75 cm diameter, 40 cm height) installed in the center of each plot to ensure representative flooded conditions. Additionally, plant parameters, notably the Leaf Area Index, were measured throughout the growing season using a LI-3100C Area Meter.

Similarly, for the 2018 and 2019 growing seasons, field data were provided from another study site within the RRII (37°16' N and 49°39' E). The current study solely utilized the LAI measurements obtained from the transplanted rice treatments of that site, where 25-day-old seedlings had been cultivated at a 20×20 cm spacing. Planting and harvesting occurred on May 24 and August 29 for the 2018 season, and May 25 and August 14 for the 2019 season, respectively. Standard regional guidelines were followed for all crop management practices, including pest and weed control.(Pouramir et al., 2020)

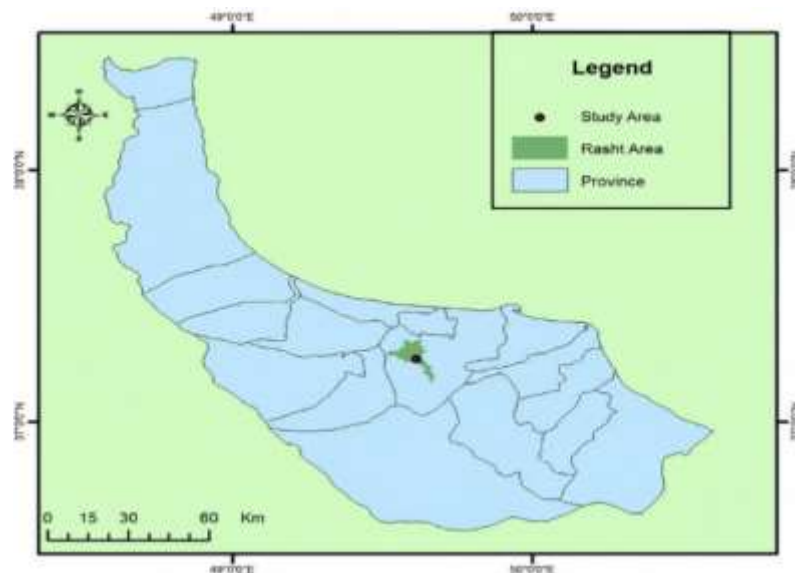


Figure 1. Location of the study area in Rasht County, Gilan Province, northern Iran.

2.2. Acquisition and processing of satellite remote sensing data

To monitor crop development and derive vegetation indices, multispectral Sentinel-2 images, along with Landsat 7 and Landsat 8 scenes, were acquired for the rice growing seasons spanning 2017 to 2019. The primary dataset consisted of Sentinel-2 Level-2A products, providing surface reflectance (SR). To address temporal gaps caused by cloud cover and to construct a dense, continuous time series, imagery from Landsat 8 and Landsat 7 was additionally incorporated into the processing pipeline. The multi-year satellite dataset was strategically partitioned to support model development and evaluation. Imagery from two consecutive growing seasons (2018 and 2019) was utilized in conjunction with corresponding field measurements to establish and calibrate the empirical relationships between the vegetation indices (NDVI and SAVI) and the Leaf Area Index. Subsequently, the satellite data acquired during the 2017 growing season was strictly reserved for independent validation. This one-year validation dataset was evaluated against the highly accurate field LAI and lysimetric actual evapotranspiration measurements to assess the final accuracy and reliability of the proposed models. A cloud filter was applied across all datasets to ensure the experimental plots were free of clouds and shadows.

2.3 Super-Resolution deep learning model (S2DR3)

The small size of agricultural fields and the native 10-m spatial resolution of Sentinel-2 bands often result in mixed pixels, which can introduce errors in vegetation index calculations. To mitigate this limitation, the S2DR3 deep learning model was used to enhance the spatial resolution of Sentinel-2 imagery from 10 m to 1 m for the 2018 and 2019 growing seasons. S2DR3 is a Convolutional Neural Network designed for Single Image Super-Resolution (SISR). Its architecture is based on the ESRGAN and employs Residual-in-Residual Dense Blocks (RRDB) to learn complex spatial and spectral patterns from the data. A self-supervised learning strategy was adopted: 10-m Sentinel-2

bands were downsampled to coarser resolutions, and the network was trained to reconstruct the original 10-m images, allowing it to capture the underlying spatial–spectral relationships without requiring external high-resolution ground truth. For operational application, the pre-trained S2DR3 model was run on Google Colab using a Tesla T4 GPU. Sentinel-2 Level-2A images were processed in 4 × 4 km tiles to generate 1-m resolution GeoTIFF outputs with 10 spectral bands. These super-resolved images were then used for more precise calculation of vegetation indices.

2.4 Estimation of LAI and actual evapotranspiration

Following the spatial enhancement of the satellite imagery to a 1 m resolution, vegetation indices were computed to assess the biophysical characteristics of the rice canopy. The NDVI and SAVI were calculated using the open-source SNAP software (version 11.0). NDVI was selected as a primary indicator of vegetation vigor, while SAVI was utilized to mitigate the influence of soil background reflectance, particularly during the early crop growth stages. To estimate the Leaf Area Index at the field scale, empirical regression models were developed. The in-situ LAI measurements collected during the 2018 and 2019 growing seasons were correlated with the corresponding satellite-derived NDVI and SAVI values to establish these predictive models. For the estimation of ET_a a crop coefficient-based approach was implemented in accordance with the FAO-56 framework. In this methodology, the K_c was first derived as a function of the satellite-estimated LAI. The ET_o was computed using the FAO-56 Penman-Monteith method based on daily local meteorological data. Finally, to assess the reliability of the proposed framework, the estimated LAI and ET_a values were independently validated against the simultaneous LAI measurements and the actual daily evapotranspiration data obtained from the four lysimeters during the 2017 experimental season.

3. RESULTS AND DISCUSSION

3.1. Evaluation of the super-resolution model (S2DR3)

The spatial resolution of Sentinel-2 images was enhanced from 10 m to 1 m using the S2DR3 deep learning model. To investigate potential spectral distortion introduced by this resolution enhancement, the Normalized Difference Vegetation Index and Soil Adjusted Vegetation Index were calculated for both the original 10 m imagery and the 1 m model outputs. Figure 1 displays the scatter plots comparing the derived vegetation indices from these two datasets. Subsequently, the datasets were quantitatively analyzed using the statistical indicators presented in Table 1. The results confirmed the absence of spectral distortion, yielding a correlation coefficient of $R^2 = 0.9979$ between the modeled NDVI and the reference 10 m NDVI.

Table 1. Statistical comparison of Sentinel-2 imagery and S2DR3 enhanced imagery (2018–2019)

Vegetation Index	Crop Year	R^2	RMSE	NRMSE	MAE
NDVI	1398	0.9979	0.012	0.028	0.010
SAVI	1398	0.9864	0.036	0.091	0.033

3.2. LAI estimation

To estimate the Leaf Area Index, empirical models were developed using both NDVI and SAVI. The calculated LAI values from each index were then directly compared with in-situ field measurements to determine which index provided a closer match to the actual ground conditions. The statistical comparison, detailed in Table 2, demonstrated that the NDVI based model generally yielded results closer to the field measurements than the SAVI based model. Across the four experimental plots, NDVI estimations resulted in RMSE values ranging from 0.187 to 0.570, whereas the SAVI model showed RMSE values ranging from 0.331 to 0.569. Although SAVI performed slightly better in Plot 3, NDVI demonstrated superior accuracy and stronger correlation overall. Based on these findings, the NDVI model was selected as the optimal index for estimating LAI and subsequently deriving the K_c .

Table 2. Statistical comparison between in-situ LAI and estimated LAI using NDVI and SAVI

Plot Number	Vegetation Index	R ²	RMSE	NRMSE	MAE
Plot 1	NDVI	0.768	0.382	0.220	0.312
	SAVI	0.720	0.569	0.328	0.416
Plot 2	NDVI	0.976	0.187	0.107	0.141
	SAVI	0.794	0.478	0.274	0.380
Plot 3	NDVI	0.840	0.570	0.392	0.481
	SAVI	0.788	0.331	0.228	0.290
Plot 4	NDVI	0.829	0.412	0.266	0.316
	SAVI	0.904	0.441	0.285	0.390

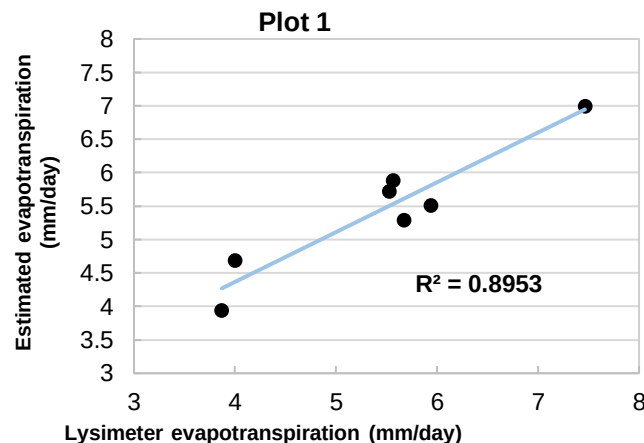
3.3. Estimation of actual evapotranspiration (ET_a)

The indirect approach for estimating ET_a using crop coefficients derived from the estimated Leaf Area Index was evaluated. In this approach, LAI values were first estimated using the Normalized Difference Vegetation Index, which demonstrated better results compared to other indices. Subsequently, the crop coefficient was calculated, and ET_a was determined. The statistical performance of the ET_a estimation models across different satellite datasets is summarized in Table 3.

Table 3. Statistical comparison between the NDVI-based model and lysimeter data

Plot No.	NDVI_R ²	NDVI_RMSE (mm/day)	NDVI_NRMSE	NDVI_MAE (mm/day)
Plot 1	0.84	0.45	0.08	0.38
Plot 2	0.89	0.4	0.07	0.36
Plot 3	0.79	0.6	0.11	0.47
Plot 4	0.86	0.58	0.11	0.52
Mean	0.85	0.5	0.09	0.43

Figure 2 illustrates the correlation between the observed and estimated ET_a values throughout the growing season. Furthermore, the seasonal cumulative evapotranspiration for the study area was estimated to be between 397 and 441 mm. The implementation of the deep learning model (S2DR3) to increase the spatial resolution of Sentinel-2 imagery to 1 meter significantly reduced the impact of mixed pixels. This improvement successfully mitigated the challenges associated with field boundaries, thereby enhancing the overall reliability of ET_a estimates for precise irrigation management



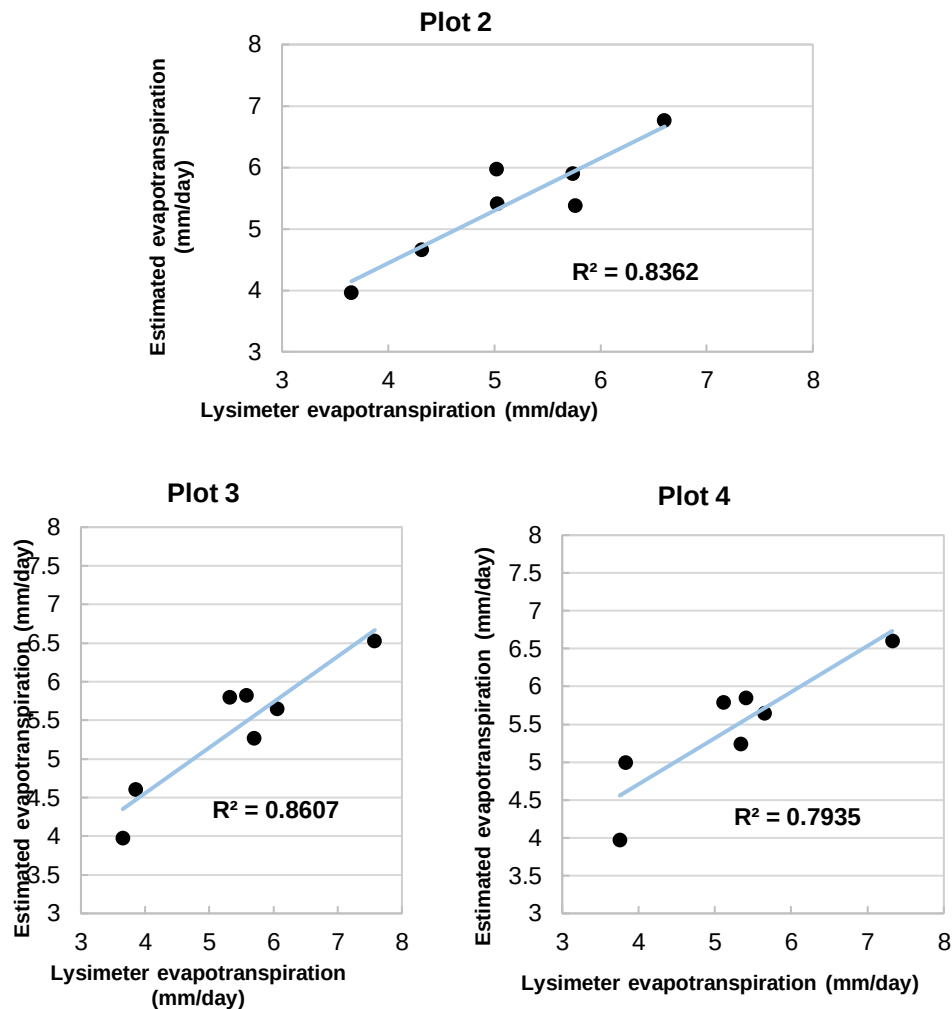


Figure 2. Comparison of daily values of NDVI-derived and lysimeter evapotranspiration data

Discussion

The accurate estimation of actual evapotranspiration in small and fragmented agricultural lands, such as the paddy fields in Guilan province, is often hindered by the mixed pixel problem in medium-resolution satellite imagery. The application of the S2DR3 super-resolution deep learning model effectively addressed this limitation by enhancing Sentinel-2 imagery from 10 m to 1 m without spectral distortion. This improvement in spatial resolution proved crucial for capturing the spatial details of the rice fields. Furthermore, the results demonstrated that utilizing the enhanced 1-m resolution imagery improved the estimation of Leaf Area Index, with NDVI showing better agreement with in-situ measurements compared to SAVI. These findings are consistent with previous research while highlighting the advantages of high-resolution imagery. For instance, compared to Jafari Seyadi et al. (2018), who reported a higher RMSE of 2.19 for LAI estimation, the reduced error in the present study (RMSE= 0.51–0.61) can be directly attributed to the mitigation of the mixed-pixel effect using 1m resolution imagery. By integrating this LAI into the FAO-56 crop coefficient approach, the study presented a practical approach for estimating ET_a at the field scale. The estimated daily ET_a values (3.8–5.8 mm/day) align with the ranges reported by Ferreira et al. (2023) and Jafari Seyadi et al. (2018), with minor differences resulting from variations in climate, rice varieties, and irrigation management. The reliability of the K_c -based approach using LAI also matches the findings of Rawat et al. (2020) and Ferreira et al. (2023), confirming its high effectiveness for accurate ET_a estimation.

Ultimately, this framework provides an operational tool for optimizing agricultural water management and irrigation scheduling in smallholder farming systems.

Conclusions

This study evaluated the practical application of the S2DR3 deep learning model to address the mixed-pixel challenge in the fragmented paddy fields of the study area. By enhancing the spatial resolution of Sentinel-2 imagery from 10 meters to 1 meter, the model served as a useful tool for maintaining spectral integrity and distinguishing the spatial details of small agricultural parcels. Utilizing these super-resolved images alongside the standard FAO-56 crop coefficient method allowed for an acceptable estimation of actual evapotranspiration at the field scale. The evaluation indicated that applying such high-resolution data to established agronomic models reduces estimation errors and provides a reasonable representation of the cumulative seasonal evapotranspiration of the rice paddies. From a practical standpoint, using super-resolution models like S2DR3 offers a cost-effective approach for agricultural water monitoring. The findings demonstrate that this approach can assist in better managing water resources and irrigation planning in regions with fragmented agricultural structures.

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