Bangladesh J. Agri. 2025, 50(1): 72-82 *DOI: https://doi.org/10.3329/bjagri.v50i1.82923*

ESTIMATION OF BORO RICE AREA IN BANGLADESH USING SENTINEL-2 IMAGERY AND MACHINE LEARNING ALGORITHMS

H. M. H. Rahman[1] and S. G. Hussain[2*]

[1]Computer & GIS Unit, Bangladesh Agricultural Research Council (BARC), Farmgate, Dhaka:
[2]Project Coordination and Partner Liaison, CSRD Project, International Maize and Wheat Improvement Center (CIMMYT). Bangladesh.

Abstract

Rice is the primary food crop in Bangladesh, and a significant portion of agricultural land is dedicated to its cultivation. Annually, approximately 36.87 million tons of rice are produced from 11.54 million hectares of land (BBS, 2021). Among the three rice seasons in Bangladesh, namely aus, aman, and boro, the winter rice boro production holds the highest percentage. Accurate delineation of boro rice-growing area is crucial for estimation of total production, which plays a vital role in policy planning and decision-making. Rice fields in Bangladesh are fragmented into smaller plots, emphasizing the importance of high-resolution, cloud-free satellite images for precise delineation of rice areas. In this context, a comparative study was conducted to estimate boro rice area in Bangladesh using high-resolution (10-meter) Sentinel-2 data, aiming to overcome the challenges posed by fragmented land. Machine Learning (ML) based supervised classification algorithms namely Decision Tree, k-Nearest Neighbor (k-NN), Random Forest (RF) and Support Vector Machine (SVM) were employed on Sentinel-2 images of the study area to identify rice fields. The study's findings are expected to contribute to the development of boro rice area estimation, predict yield and productivity system in Bangladesh, ultimately enhancing food security and the livelihood of farmers.

Keywords: Area Delineation, Boro rice, Machine learning , Sentinel-2 imagery, Yield forecasting.

Introduction

Over the past five years (2018-19, 2019-20, 2020-21, 2021-22, 2022-23), Bangladesh has consistently produced an average of 37.45 million tons of rice annually from an area of 11.59 million hectares (BBS, 2022). Accurately delineating the boro rice area holds immense importance in national-level production planning as it enables the development of an accurate yield forecasting system and facilitates rice growth monitoring. Failure to achieve accurate estimations can lead to crop losses, unfair pricing, and other detrimental consequences for farmers. Additionally, policymakers face challenges in planning export/import activities and formulating appropriate farming strategies, resulting in significant economic losses for both farmers and the nation. To address these challenges,

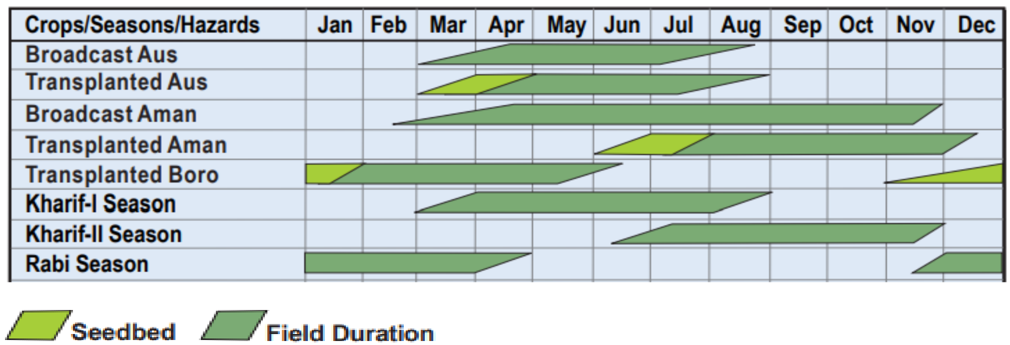
* Corresponding author: h.rahman@barc.gov.bd

this study was conducted utilizing high-resolution (10-meter) Sentinel-2 satellite data to delineate boro rice cultivation areas. By leveraging Sentinel-2 optical satellite data and employing four machine learning algorithms, the study seeks to compare the performance of different algorithms in accurately delineating rice areas within the context of Bangladesh. Recent advancements in remote sensing technology, particularly satellite imagery, have provided valuable tools for monitoring and estimating crop areas. High-resolution and cloud-free images have shown great potential in accurately identifying and delineating agricultural areas. The Sentinel-2 satellite offers multi-spectral imagery with a spatial resolution of 10 meters, making it well-suited for detailed land cover classification. As the boro rice grows in winter season, therefore cloud free images are expected to be available during the season. Machine learning algorithms have also gained prominence in the field of remote sensing analysis. These algorithms, when trained with labeled satellite imagery, can effectively classify land cover types, including crops such as rice. By harnessing the capabilities of machine learning and utilizing Sentinel-2 imagery, it becomes possible to develop a reliable and efficient system for estimating the boro rice area in Bangladesh. Several studies have contributed to the field of rice area estimation using remote sensing technology (Setiyono *et al., 2018).* demonstrated the operational capability of a system developed by the RIICE project, conducting an extensive evaluation of its performance in key rice-growing areas across South and Southeast Asia (Nelson *et al.,* 2014). In Bangladesh, MODIS images were utilized to detect changes in rice cultivation, focusing on the phenological study of five districts: Pabna, Manikganj, Sherpur, Sylhet, and Gazipur (Setiyono *et al.*, 2018). The Bangladesh Space Research and Remote Sensing Organization (SPARRSO) has predominantly employed MODIS data to monitor aman and boro rice, with the satellite TERRA being utilized for this purpose (Rahman, H., 2014). Additionally, the area delineation under rice cultivation has been carried out using GIS-based crop suitability maps, as demonstrated (Hussain *et. al.,* 2012). It is important to note that the approach did not involve remote sensing technology, potentially leading to discrepancies between the calculated rice area from the suitability map and the actual area coverage.

Nelson *et al.(*2014) combined moderate-resolution (100-meter resolution with a revisiting time of 16 to 24 days) time series data from Synthetic Aperture Radar (SAR) and MODIS optical sources (with a resolution of 500 meters) for rice crop characterization in Bangladesh. SAR and MODIS were employed for rice area mapping and seasonal monitoring within the delineated area, respectively, to overcome spatio-temporal challenges and establish an operational monitoring system. Singha *et al.(* 2019) conducted paddy rice mapping in Bangladesh and Northeast India using Sentinel-1 data and Random Forest (RF) classification. However, their study lacked a comparison with other supervised classification methods. In a similar vein (Rudiyanto *et al.,* 2019) developed an automated near-real-time mapping and monitoring system for rice extent, cropping pattern, and growth stages using Sentinel-1 time series in Southeast Asia, utilizing the Google Earth Engine (GEE) platform. They integrated temporal Sentinel-1 data with phenological parameters in GEE and employed K-means clustering, Hierarchical Classification Analysis (HCA), and visual image interpretation to generate rice extent, cropping patterns, and spatiotemporal distribution of growth stages. The study automated the classification process using multiple machine learning algorithms and compared the results. In this study, we employed supervised classification algorithms such as Classification And Regression Tree (CART), k-Nearest Neighbor (k-NN), Random Forest (RF) and Support Vector Machine (SVM) for boro rice area delineation which are popular for image classification. By utilizing Sentinel-2 imagery and using these algorithms, we aim to contribute to the understanding of their performance in accurately estimating rice areas in Bangladesh. The successful implementation of an efficient boro rice area estimation system will have significant implications for policy planning, allocation of agricultural resources, and ensuring food security in Bangladesh. The objective of this study is to assess the potential of Sentinel-2 imagery and machine learning algorithms in more accurately estimating the boro rice areas in Bangladesh. By leveraging high-resolution satellite imagery and implementing supervised classification algorithms, the research aims to address the challenges posed by fragmented rice fields. The outcomes of this study will not only provide valuable insights into the extent of boro rice cultivation but also contribute to the development of in-season yield forecasting and end-of-season yield estimation systems.

Rice scenario in Bangladesh

There are three distinct rice seasons in Bangladesh known as aus, aman, and boro, each with its unique characteristics. Aman is considered a wet season, while boro and aus are categorized as dry seasons due to their overlapping cultivation (Fig. 1). The following is a summary of the three rice seasons based on the information provided by Maki *et al.*, 2017. Aus rice, classified as a kharif-I crop, is predominantly direct-seeded during the months of March and April, with harvesting taking place in July and August. The cultivars in this group mature irregularly and are not influenced by photoperiod changes. Although typically rain-fed and dry-seeded, Aus rice can also be transplanted when there is sufficient rainfall and irrigation available. Farmers opt for Aus as a short-duration drought-resistant crop during the pre-monsoon period of March to May. Transplanted Aus rice seedlings are raised in March and April, with harvesting occurring in July and August. Typically, the crop is transplanted using seedlings that are 20-30 days old. Local varieties are commonly preferred during the Aus season, but recently, farmers have started cultivating modern short-duration varieties as well. Aman, categorized as a kharif-II crop, is sown during the rainy season (July-August) and harvested in November and December. Aman rice can either be directly broadcasted or transplanted. In Bangladesh, broadcast aman rice is also known as deep water rice (DWR). Traditionally, it is directly seeded from March to May, which is the pre-monsoon period, in land that is deeply flooded (1-4 meters). However, due to changes in cropping patterns, transplantation is also carried out between May and June. In both cases, once the crop is established, the plants grow as the floodwater rises from June to September. Aman rice is sensitive to photoperiod changes and is harvested after the floodwater recedes, typically in November and December. Transplanted aman rice refers to traditional photoperiod-sensitive rice varieties that are transplanted in July and August, with harvesting taking place in November and December. Recently, photoperiod-insensitive varieties have become available in Bangladesh, and farmers have started cultivating them during the transplanted aman season. On land with shallow flooding depth, aman rice is transplanted using shorter duration varieties. Boro, classified as a rabi crop, is transplanted during the winter season and harvested in summer. With the widespread use of groundwater irrigation, this group of photoperiod-insensitive irrigated rice can now be grown on all types of land. Boro rice is mainly transplanted in January and February, with harvesting taking place in May and June. Previously, farmers used to grow boro rice in very low-lying lands that were unsuitable for cultivating any crop during the monsoon season. After the floodwaters recede, boro rice is transplanted in November and harvested in April and May.



Source: *Hussain 2017*

Fig. 1. Rice calendar with cropping season in Bangladesh

Materials and Methods

Satellite image

This study utilizes the optical data from the European earth observation satellite Sentinel-2, which is accessed through the Google Earth Engine (GEE) platform. First, a Region of Interest (RoI) is selected to cover the entire country of Bangladesh. Then a stack of Sentinel-2 (COPERNICUS/S2_SR) images is created for boro rice, and spatio-temporal image filtering is performed on the stack based on the rice calendar. Consequently, time series Sentinel-2 images are used for boro rice during December 2020 to March 2021 and the field data collection took place during that time. The winter season in tropical regions like Bangladesh, when boro rice is grown, typically has fewer clouds, making Sentinel-2 data suitable for identifying boro rice areas. However the Sentinel image filtered out with the cloud above 20%.

Field/signature data

Field data collection is crucial for rice area classification using machine learning models. Sample locations for data collection are selected based on the boro rice-growing areas. Handheld GPS devices are used to capture point (latitude, longitude) and polygon data for rice, other crops, settlements, water bodies, etc., during the collection of signature data. Boro rice signatures are collected between December 2020 and March 2021. Four machine learning algorithms are applied separately for boro rice area estimation.

ML algorithm in GEE

In GEE, the CART, k-NN, Random Forest and SVM models are represented by the smileCart(), smileKNN(), smileRandomForest() and libsvm() functions, respectively, which are used to calculate the boro rice area. The field datasets are divided into 80% for model training and 20% for validation (accuracy assessment). The training and validation datasets ensure a proportionate representation of each land cover category. The accuracy levels of different algorithms are compared, and the most accurate output is selected as the final boro rice area. The accuracy is obtained from confusion matrix. At the same time, the area of boro cultivation generated by Machine Learning classification is compared with BBS data.

Methodology of Boro rice area delineation

The methodology for boro rice area delineation is illustrated in the diagram in Fig.2

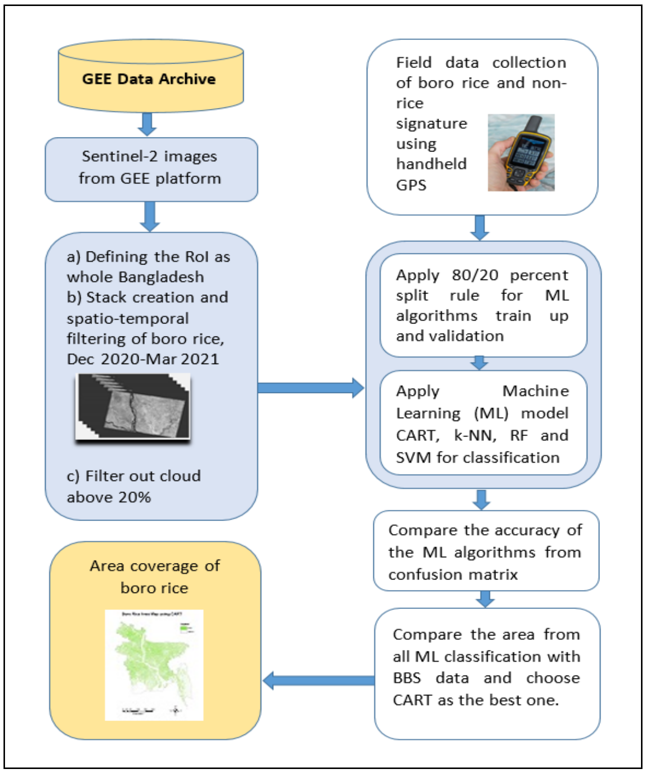


Fig. 2. Methodology of boro rice area delineation

Data collection

Quantitative and qualitative data were collected from in-situ rice fields, which served as the rice signature for the study. Questionnaires were developed for data collection and they were pretested in various locations during the boro season, and necessary adjustments were made based on the results of the experimental survey. To capture the location data, handheld GPS devices were used for each sample. The questionnaire comprised 29 parameters, including GPS coordinates, on which the survey was conducted. For field data collection, GPS locations were recorded from all directions around the plot to create polygon data. Point data were collected from inside the field. Additionally, photos of the fields were captured using a digital camera. The farmer or, in some cases, the landowner was interviewed to gather relevant information about the crop or rice. This information included details about the farmer, crop or rice variety, seedling and planting dates, irrigation practices, fertilizer usage, pesticide application, yield from the previous year, and other related information.Sample locations for boro rice fields were selected based on the rice production areas throughout Bangladesh. Data on rice production at the district and Upazila level were obtained from the annual yearbook of agricultural statistics published by the Bangladesh Bureau of Statistics (BBS). The survey for boro rice was conducted from December 2020 to March 2021, covering a total of 606 locations across Bangladesh, including 205 rice signatures and 401 non-rice signatures. The non-rice signatures included other crops, settlements, rivers, water bodies, brick fields, and so on. The table below provides further information on the sample data collected for boro rice:

Table 1. Field survey information

Rice	Survey extent	Survey duration	No. of rice sample	No. of non-rice sample (other crop, settlement, rivers, water bodies etc.)	Total no. of sample
Boro	All over Bangladesh	December 2020 to March 2021	205	401	606

Data processing

The field data collected during boro seasons are compiled into an Excel sheet. Some conversions of measurement units, such as land size, fertilizer and pesticide application quantities, etc., are necessary to maintain a consistent format for the data. A desk validation process is conducted to verify the captured data, and any missing data are filled in by contacting the farmers via mobile phone in most cases. The validated data is then saved as a CSV file, which serves as the attribute file.The survey locations are shown in Fig. 3. Simultaneously, the GPX file from the handheld GPS devices is downloaded and imported into Google Earth Pro to verify the survey locations. Polygons are drawn using the GPS points and digital photos for most of the fields. The file is exported in KML format and opened in QGIS, where it is converted into a shapefile. The shapefile is then joined with the attribute file (CSV) to merge the land types and other parameters. Non-rice land types are generalized into a single class called 'non-rice'. In the shapefile, there are two columns named 'id' and 'feature_name', where the value of id equals '0' represents 'non-rice' and '1' represents ‘rice’ features. The generalized shapefile is imported into the Google Earth Engine (GEE) asset, where it is used as the signature data in the machine learning (ML) model.

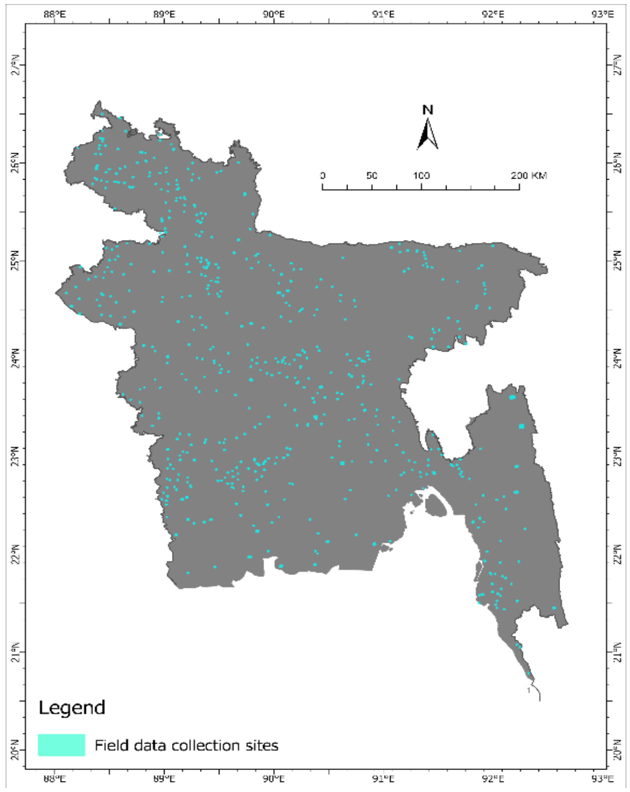


Fig. 3. Sample location of boro rice data collection (606 signatures)

Results and Discussion

The delineation of boro rice areas has been conducted using Sentinel-2 images, followed by the methodology discussed in the previous section. Four supervised machine learning algorithms CART, k-NN, RF and SVM have been employed and the resulting rice area is depicted in Fig. 4. The estimated area of Boro rice, derived using the CART, k-NN, RF, and SVM algorithms, along with the corresponding data from the Bangladesh Bureau of Statistics (BBS), is presented in Table 2. The overall classification accuracies for Boro rice using CART, k-NN, RF, and SVM were 96%, 97%, 97%, and 85%, respectively. These results indicate that all algorithms, except SVM, achieved high accuracy in identifying rice cultivation areas. Among them, k-NN and RF demonstrated the highest accuracy (97%) for Boro rice area classification. According to Table 2, the total rice area estimated by the CART algorithm is 4,199,579 hectares, which shows the smallest deviation (12%) from the BBS-reported area of 4,786,621 hectares. Therefore, the map generated using the CART algorithm is considered the best representation of the Boro rice area for the 2020-21 season.

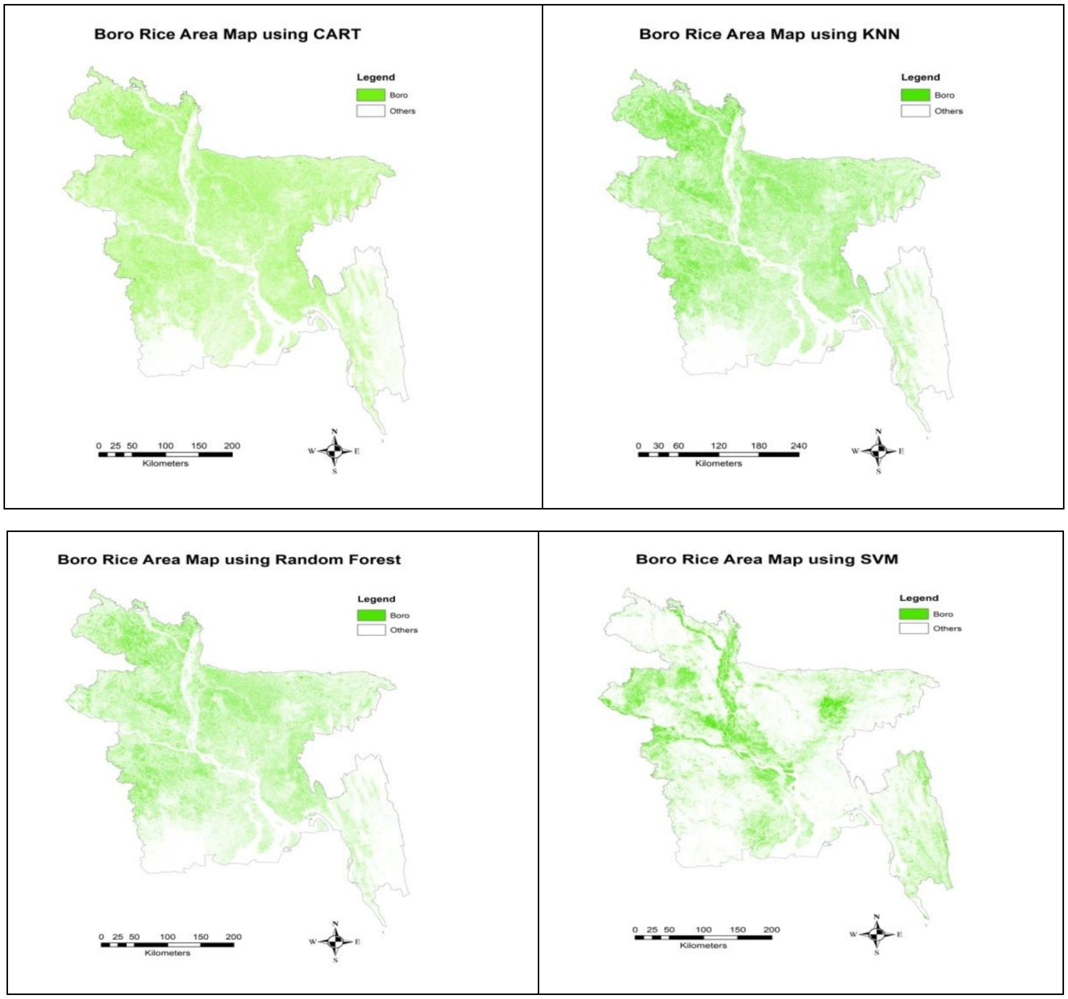


Fig. 4. Boro rice area generated by CART, k-NN, RF and SVM algorithm

Table 2. Boro rice area generated by CART, k-NN, RF, SVM and BBS 2021

Sl.	Classification Algorithm	Pixel count (10m x 10m)	Area in Sq. Meter	Area in Sq. km	Area in ha	Classification Accuracy of Algorithm (%)	Deviaton from BBS (%)
1	CART	419957945	41995794500	41996	4,199,579	96	12
2	k-NN	384058603	38405860300	38406	3,840,586	97	20
3	RF	295960922	29596092200	29596	2,959,609	97	38
4	SVM	240296058	24029605800	24030	2,402,961	85	50
BBS Statistics (2020-21)					4,786,621	-	-

In this study, all classes except for rice have been generalized into a single class called 'non-rice'. This approach contributes to improving the overall accuracy of the classification algorithms. Based on the conducted work following the proposed methodology, the CART algorithm is deemed more effective for the delineation of boro rice areas in Bangladesh using Sentinel-2 imagery. Bangladesh has mainly three rice growing seasons namely aus, aman and boro. Among them boro rice is grown on irrigated condition in Bangladesh and is vulnerable to flash flood damages thereby reducing rice yields (Hossain *et al.*, 2021). Previously, several efforts have been made to enumerate rice area using differnt field-based sampling globally (Xiao and He, 2021) but these methods required high cost and is also time-consuming. Scientist also applied RS based system such as optical and synthetic aperture radar (SAR) datasets for observing and mapping rice crops (Zhao *et al.*, 2021). RS based system can be divided into two broad groups, one is machine learning (Blickensdörfer *et al.*, 2022) and other is phenology-based threshold delineation (Xiao and He, 2021). Sentinel-1 and Sentinel-2 (S1, S2) were extensively used to map rice and quantify rice crop loss in Bangladesh (Islam *et al.*, 2022). Banngladeshi scientist also applied algorithms based single images (Alam *et al.*, 2019) as well as time-series imagery (Aziz *et al.*, 2023) to mapped the rice areas in Bangladesh.

This study delineated boro rice cultivation areas across Bangladesh using a limited number of signature points (606), which may slightly affect the accuracy of the method. However, the estimated Boro rice area deviates by only 12% from the BBS report, making it the most reliable model given that no such comprehensive effort has been undertaken in Bangladesh using Google Earth Engine (GEE) and Sentinel data at no cost (utilizing free 10m × 10m Sentinel-2 data from the GEE platform). In contrast, RF and SVM significantly underestimated the rice area.Generalizing all non-rice land types into a single 'non-rice' class improved classification performance by minimizing spectral. Despite using a modest sample size (606 points), the nationwide application demonstrated that high-resolution imagery combined with ML can provide accurate, cost-effective, and scalable rice area estimations. Furthermore, the successful application of Sentinel-2 imagery and the CART algorithm in this study provides a replicable framework for similar crop mapping initiatives in other regions, particularly where land fragmentation presents a challenge to conventional survey-based approaches. The integration of high-resolution satellite data with advanced classification models thus represents a transformative step forward in agricultural monitoring and food systems planning in Bangladesh.These findings support the integration of remote sensing and ML for crop monitoring, policy planning, and food security strategies, and establish a baseline for future enhancements using multi-temporal or multi-sensor data.

Conclusion

Accurate rice area mapping is critically important for yield forecasting, a task that can be both labor-intensive and error-prone when done manually. Satellite image-based delineation of rice areas provides a valuable alternative and is increasingly recognized as an effective approach for both present and future agricultural monitoring. Given the fragmented nature of agricultural land in Bangladesh, high-resolution satellite imagery offers enhanced capabilities for rice monitoring and yield prediction. In this study, rice area maps covering 4,199,579 hectares were generated using 10-meter resolution Sentinel-2 imagery. The machine learning algorithm CART (Classification and Regression Trees) was found to be the most effective in generating these results. These maps, when combined with data on climate, soil conditions, crop genetics, and crop management practices, can be integrated into crop models to improve the accuracy of yield and production forecasts. In-season yield forecasting systems that utilize satellite imagery can deliver vital insights to a range of stakeholders, including farmers and policy planners.

Acknowledgment

We sincerely thank Md. Mahmudul Hasan and Md. Jahir Uddin Omar for their dedication in data collection, Md. Mustafa Kamal (CIMMYT) for technical support, Md. Rafique Ahasan Chawdhery and Md. Abdullah Al Baki for their valuable inputs, and the farmers for sharing their time and insights.

Author's contributions

Both authors contributed equally to the manuscript. They jointly conducted the literature review, analysis, and content organization. The first author prepared the final draft, which was reviewed and approved by the second author before submission.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this manuscript.

References

Alam, M. S., Kalpoma, K., Sanaul, K., Abdullah, K., and Jun, I. 2019. Boro rice yield estimation model using modis ndvi data for Bangladesh. In: IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium, 7330-33. IEEE, Yokohama, Japan.

Aziz, M. A., Haldar, D., Danodia, A., and Chauhan, P. 2023. Use of time series sentinel-1 and sentinel-2 image for rice crop inventory in parts of Bangladesh. Appl. Geomatics. https://doi.org/10.1007/s12518-023-00501-2.

BBS (Bangladesh Bureau of Statistics). 2021. Statistical Yearbook Bangladesh 2020. Bangladesh Bureau of Statistics, Ministry of Planning, Government of the People's Republic of Bangladesh, Dhaka.

BBS (Bangladesh Bureau of Statistics). 2022. Statistical Yearbook Bangladesh 2021. Bangladesh Bureau of Statistics, Ministry of Planning, Government of the People's Republic of Bangladesh, Dhaka.

Blickensdorfer, L., Schwieder, M., Pflugmacher, D., Nendel, C., Erasmi, S., and Hostert, P. 2022. Mapping of crop types and crop sequences with combined time series of sentinel-1, sentinel-2 and Landsat 8 data for Germany. *Rem. Sens. Environ*. 269, 112831

Ferencz, C., Bogna, P., Lichtenbarger, J., Hamar, D., Tarchia, G., Tima, G., Molna, G., Sztor, P., Steinbach, B., Ferencz, O. E., and Ferencz-r, I. 2004. Crop yield estimation by satellite remote sensing. *Int. J. Remote Sens*. 25 (20):4113-4149.

Hirooka, Y. K., Homma, M. M., and Sekiguchi, K. 2015. Applicability of synthetic aperture radar (SAR) to evaluate leaf area index (LAI) and its growth rate of rice in farmers' fields in Lao PDR. F. *Crop. Res.* 176:119-122.

Hossain, M., Khan, M. H. R., and Islam, M. S. 2021. Impacts of heat stress on mineral nutrition of boro rice cultivar (BR 19) as influenced by the indigenous organic fertilizers. *Dhaka Univ. J. Biol. Sci.* 30(1):125-131.

Hussain, S. G. 2017. Identification and modelling of suitable cropping systems and patterns for saline, drought and flood prone areas of Bangladesh. Christian Commission for Development in Bangladesh. Climate Change Unit. pp.140.

Hussain, S. G., M. K., Chowdhury, A., and Chowdhury, M. A. H. 2012. Land Suitability Assesment and Crop Zoning of Bangladesh. BARC, Dhaka, Bangladesh.

Islam, M. M., Matsushita, S. N., Ryozo, A., and Tofael. 2022. A damage-based crop insurance system for flash flooding: a satellite remote sensing and econometric approach. *Asia-Pacific J. Reg. Sci.* 6(1):47-89.

Maki. M., *et al.* 2017. Rice yield estimation using synthetic aperture radar (SAR) and the ORYZA crop growth model: development and application of the system in South and South-east Asian countries. *J. Agri. Meteorol.* 73(1):8093-8124.

Nelson, A., Setiyono, T., Arnel, B. R., Emma, D. Q., Jeny, V., Prosperidad, J. A., Aileen, A. M., Cornelia, A. G., Hannah, Z. M. B., Lorena, S. V., Pongmanee, T., Francesco, H., Massimo, B. *et al.* 2014. “Towards an operational SAR-based rice monitoring system in Asia: Examples from 13 demonstration sites across Asia in the RIICE project. *Remote Sens.* 6(11):10773-10812.

Rahman, H. 2014. Satellite Based Crop Monitoring and Estimation System for Food Security Application in Bangladesh, Crop Monit. Improv. Food Secur. pp.1-16.

Rahman, A., Khan, K., Krakauer, N. Y., Roytman, L., and Kogan, F. 2012. Use of Remote Sensing Data for Estimation of Aman Rice Yield. *Int. J. Agri. For*. 2(1):101-107.

Rudiyanto, B., Minasny, R. M., Shah, N. C., Arif, S. C., and Setiawan, B. I. 2019. Automated near-real-time mapping and monitoring of rice extent, cropping patterns, and growth stages in Southeast Asia using Sentinel-1 time series on a Google Earth Engine platform. *Remote Sens*.11(14):1-27.

Setiyono, T. D., Quicho, E. D., Holecz, F. H., Khan, G. Romuga, N. I., Maunahan, A., Garcia, C., Rala, A., Raviz, J., Collivignarelli, F., Gatti, L., Barbieri, M. , Phuong, D. M., Minh, V. Q., Intrman, Q. T. P., Rakwatin, M., Sothy, T., Veasna, S. P., and Mabalay, M. R. O. 2018. Spatial rice yield estimation based on MODIS and Sentinel-1 SAR data and *Oryza* crop growth model. *Remote Sens*.10(2):1-20.

Shapla, T., Park, J., Hongo, C., and Kuze, H. 2015. Change Detection of Rice Cultivation in Bangladesh Based on the Phenological Analysis of MODIS Data. *Adv. Remote Sens.* 4(4):319-329.

Singha, M., Dong. J., Zhang. G., and Xiao, X. 2019. High resolution paddy rice maps in cloud-prone Bangladesh and Northeast India using Sentinel-1 data. *Sci. Data*. 6(1):1-10.

Xiao, S. X., and He, T., 2021. Mapping paddy rice with Sentinel-1/2 and phenology-, object-based algorithm a implementation in hangjiahu plain in China using GEE platform. *Rem. Sens.* 13(5):990.

Zhao, R., Li, Y., and Ma, M. 2021. Mapping paddy rice with satellite remote sensing: a Review Sustainability. 13(2):503.