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Remote sensing applied to cocoa crop identification, a thematic review

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ABSTRACT

This article presents a thematic review of 25 publications related to the use of remote sensing techniques for the identification of cocoa crops from 2000 to 2023. Although the use of remote sensing techniques is widely used for mapping different covers because it is very useful in discriminating them, the generation of maps of cocoa crops presents challenges due to their spectral behavior similar to that of forests. This is because cocoa cultivation, being an agroforestry system that is developed in association with timber trees, causes the classification algorithms used to fail to differentiate between forest cover and cocoa crops. For this reason, this study seeks to investigate the different remote sensing techniques used in the mapping of cocoa crops, as well as an analysis of the structure of the publications highlighting the connections between countries and the factors that motivated the authors to research this crop.

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1. INTRODUCTION

Currently, cocoa in Colombia is positioned as a crop with an economic impact and that encompasses a social component associated with its impact in conflict zones since it is implemented as an alternative to illicit crops in the country. In Colombia, cocoa is produced mostly by small and medium-sized farmers amounting to 38,000 families, achieving an annual production of 60,000 tons, which makes it a source of income [1]. Cocoa cultivation in some countries has a high proportion of forest loss, such as Ghana (25%), Ivory Coast (21%), the two largest cocoa producers in the world, and Liberia (15%) [2], [3]. Due to the deforestation problem that occurs in the main cocoa-producing countries, regulation 2023/1115 [4] was approved, known as the zero deforestation regulation, which is part of the green deal initiatives to promote actions that address climate change and protect the environment [5]. According to the regulation, no cocoa product can enter or leave the European Union (EU) market if deforestation or forest degradation occurs after December 31, 2020 [6]. To identify deforested areas, remote sensing and its different techniques have been useful, from the different studies on land use and cover [7]. Regarding cocoa cultivation, [8], it is carried out in association with service trees, whether fruit trees, timber trees, or a combination of these, which provide shade during their phenological development, which is why cocoa plantations have a great similarity with natural forests, making the process of classifying cocoa cover difficult due to the similarity between the spectral signatures of the covers [9]. Given the above, the objective of this article is to present a thematic review of the scientific production of remote sensing techniques that have allowed for the classification

processes of cocoa crops. It is expected that the results obtained will be an input in the search for remote sensing techniques that support compliance with regulation 1115 EUDR.

2. METHOD

2.1. Review structure

The study of bibliographic data using statistical and numerical tools is called bibliometry and can be used to analyze patterns of scientific publications on a specific topic [10]. The bibliometric analysis was carried out with the bibliometrix package [11] in R using the biblioshiny graphical interface to facilitate interaction with the user and the visualization of the analyzed data. The PRISMA methodology in Figure 1 was applied to have a logic for analyzing the documents, which would allow applying inclusion and exclusion criteria [12], [13].

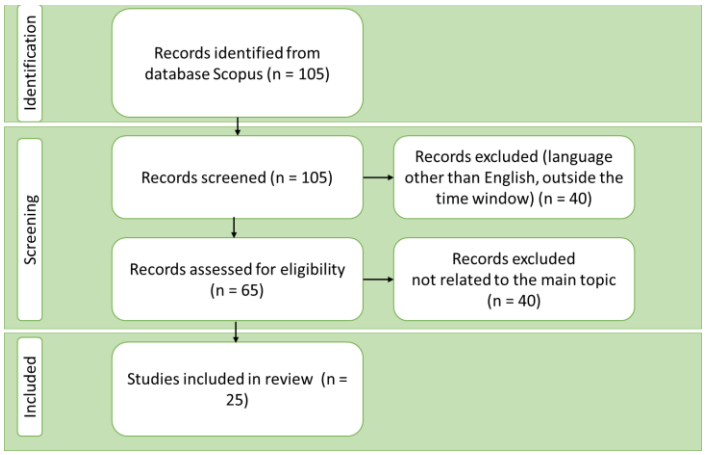

Figure 1. PRISMA applied methodology

2.2. Data collection

The reference base consulted was Scopus, in the time window defined for the analysis was from the year 2000 to 2023. The search equation applied was ("Land cover types" OR "Land change" OR "Land cover dynamics" OR "Land cover" OR "Land use") AND ("remotely sensing" OR "maps" OR "mapping" OR "classification" OR "remote sensing" OR "GIS" OR "Multiespectral" OR "imagery" OR "satellite images") AND ("cacao" OR "cocoa" OR "theobroma cacao" OR "cocoa plantations" OR "cocoa agroforetrsy" OR "cocoas"). With this equation, it was possible to detect 105 records in SCOPUS, to which the following exclusion criteria were applied: i) records in a language other than English, ii) records outside the time window, and iii) records that when reviewed were not related to the main topic. Once the exclusion criteria were applied, 25 documents were obtained to carry out the thematic review.

3. RESULTS AND DISCUSSION

3.1. Geography distribution of authors

Figure 2 shows that countries such as Ghana, Germany, and Brazil have the largest number of authors. The number of authors per country ranges between 8 and 26, with Ghana (26) having the largest number of authors, followed by Germany (12) and Brazil (8). The countries mentioned have a strong connection with cocoa cultivation. Ghana, located on the African continent, is one of the countries with the largest cocoa production worldwide [14] while Germany is one of the main importing and exporting countries of cocoa [15]. Although Germany is not a producing country, it is familiar with all cocoa manufacturing, adding value through its processing for the production of chocolates and other cocoa-derived products that are exported worldwide. For its part, Brazil is considered the main producer of cocoa in Latin America, being one of the main ones worldwide [16]. However, it should not be overlooked in this scenario that countries such as the Netherlands and Cameroon, followed by China and Mexico, play a crucial role with 7 and 6 authors respectively, which stand out worldwide for their participation in the cocoa market. China is one of the Asian countries with the highest cocoa production and manufacturing, and the Netherlands and Mexico are some of the countries with the highest participation in cocoa manufacturing issues worldwide.

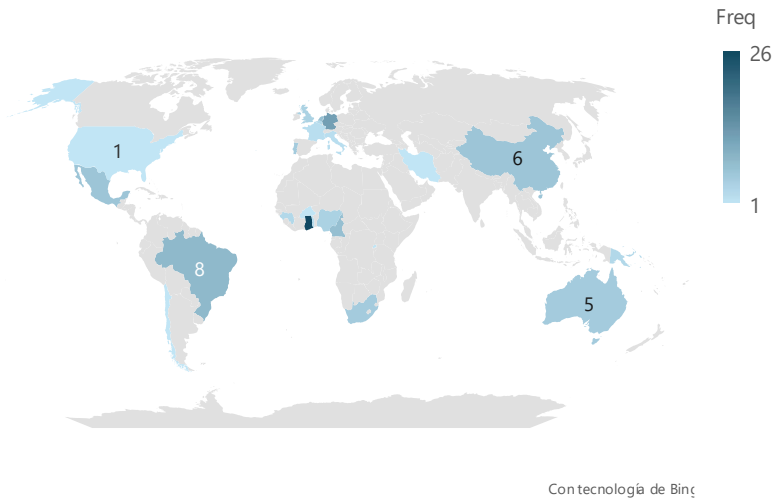

Figure 1. Authors by country

3.2. Publication by year

Analyzing the annual variation of publications, see Figure 3, it was possible to show that up to 2017, 20% of total productivity was generated, and in 2018 alone, 16% of productivity was recorded, that is, only 4% less than what was achieved in 12 years. Since 2017, an upward trend has been observed in scientific research developed on the subject. By delving a little deeper into the subject, some facts were identified that could motivate such behavior. In 2017, important initiatives began to be generated that motivated the production of sustainable cocoa during the negative effects of climate change and premium chocolate trends driven by the market. By 2018, the commitment of cocoa-producing countries to combat deforestation and the creation of international agreements such as the Cocoa & Forests Initiative gave way to the adoption of practices that encouraged more sustainable cocoa production. And at the commercial level, the tension between the United States and China impacted the markets for basic products, including cocoa, affecting its prices.

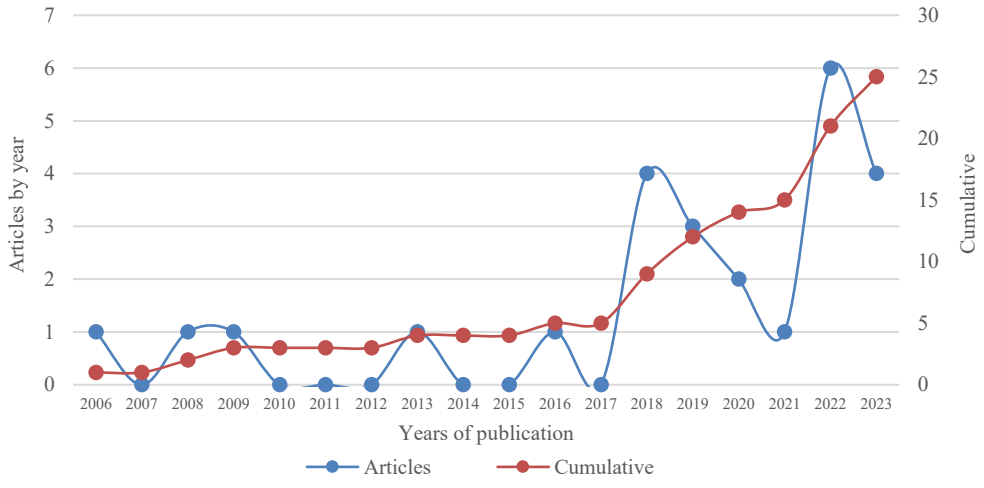

Figure 3. Temporal distribution of articles between 2006 and 2023

3.3. Most relevant articles

According to the results obtained, the 10 most cited articles can be seen in Table 1. These showed that the main topics addressed in the publications were mainly related to the problem of deforestation, land use and land cover, as well as the countries associated with this problem, Ghana and Cameroon.

Table 1. The most relevant articles

Title	Year	Journal	Total Citations
Cocoa crops are destroying the forest reserves of the classified forest of Haut-Sassandra (Ivory Coast)	2016	Global Ecology and Conservation	63
Regional land cover mapping in the humid tropics using combined optical and SAR satellite data—a case study from Central Sulawesi, Indonesia	2009	International Journal of Remote Sensing	58
Delineation of Cocoa Agroforests using Multiseason Sentinel-1 SAR images: a low grey level range reduces uncertainties in GLCM texture-based mapping	2019	International Journal of Geo - Information	46
Effects of tree-crop farming on land-cover transitions in a mosaic landscape in the Eastern Region of Ghana	2018	Environmental Management	36
Detecting cocoa plantations in Côte d'Ivoire and Ghana and their implications on protected areas	2021	Ecological Indicators	32
Change vector analysis to categorize land cover change processes using the tasseled cap as biophysical indicator	2008	Environmental Monitoring and Assessment	25
An assessment of land-use changes in the Cocoa Belt of south-west Nigeria	2013	International Journal of Remote Sensing	19
Investigating relationships between Landsat-7 ETM+ data and spatial segregation of LULC types under shifting agriculture in southern Cameroon	2006	International Journal of Applied Earth Observation and Geoinformation	17
Spatial and temporal dynamic of land-cover/land-use and carbon stocks in Eastern Cameroon: a case study of the teaching and research forest of the University of Dschang	2018	Forest Science and Technology	16
Pixel-based and object-oriented approaches in segregating cocoa from forest in the Juabeso-Bia landscape of Ghana	2020	Remote Sensing Applications: Society and Environment	13

3.4. Thematic review

Table 2 (in Appendix) presents the main findings of the thematic review associated with each of the 10 most relevant articles. From Table 2, it can be concluded that four of the 10 most cited articles carried out their study using optical and radar satellite images, of which the study carried out by [17] obtained an accuracy of 89%, being the highest of the group of articles analyzed. Regarding the precision algorithms used, the majority was the maximum likelihood algorithm with quite good accuracies, all above 80%. Three of the four studies that used optical and radar images as inputs used the random forest (RF) algorithm with which the highest precision mentioned above was obtained, however, the remaining study used the k-nearest neighbor (kNN) algorithm with which it obtained an accuracy of 69%, this being the lowest of the 10 articles analyzed. On the other hand, the main motivation for the development of the studies was to identify the dynamics of land use in forest areas since cocoa cultivation is associated with deforestation processes.

4. CONCLUSION

Although there are different methods to identify cocoa crops, the studies that used the combined use of optical and radar images with the Random Forest algorithm were the ones that obtained the highest precision (89%). On the other hand, although the cocoa publications in the range of years analyzed are relatively low (25), a growing trend is evident from 2017 onwards, which is likely to be driven by the new regulations and guidelines on environmental conservation that will require the implementation of advanced technologies for the efficient monitoring of these dynamics. In terms of publications, although a fairly diverse geographical distribution was observed, it is observed how each of these countries plays a crucial role in the cocoa production chain, either as producing countries or in cocoa manufacturing processes, a behavior that is directly related to the degree of participation of each country in the said chain.

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APPENDIX

Table 2 presents the main findings of the thematic review associated with each of the 10 most relevant articles (*continue*)

Title	Reference	Methodology	Findings
Pixel-based and object-oriented approaches in segregating cocoa from forest in the Juabeso-Bia landscape of Ghana	[17]	Data from Sentinel-1 and Sentinel-2 satellites were used to generate three data sets: spectral bands, vegetation indices, and image objects derived using a multi-resolution segmentation algorithm. These data sets were then classified using the Random Forest algorithm. The accuracy of the classifications was assessed, and the McNemar test was used to compare statistical differences between the data sets.	The classification performed with the third dataset, which integrated spectral bands, backscatter data, and image objects, had an accuracy of 89.76% and a kappa coefficient of 0.877. This set was the most effective in differentiating agroforestry cocoa from open canopy forest, outperforming other sets that presented accuracies of 79.02% and 80.49%. Image objects were identified as the most relevant predictors to increase classification accuracy.
An assessment of land-use change in the Cocoa Belt of south-west Nigeria	[18]	The study uses multispectral satellite imagery to analyze land use and land cover changes in the Cocoa Belt in southwestern Nigeria over 25 years. Landsat TM and ETM+ images from 1986, 2002, and 2011 were used. Image classification was performed using a maximum likelihood (MLC) algorithm, which identified	The study reveals significant land use changes in the Cocoa Belt of Nigeria between 1986 and 2011. During this time, built-up areas increased by 86.32% and gallery vegetation by 43.12%, while cultivated land and forest cover decreased by 16.91% and 0.96%. The conversion of agricultural and forest land to built-up areas

Table 2 presents the main findings of the thematic review associated with each of the 10 most relevant articles (*continue*)

Title	Reference	Methodology	Findings
		categories such as built-up areas, forest cover, water bodies, and cultivated land. Field visits were conducted to validate the data and ensure the accuracy of the classifications, in addition to analyzing the spatial and temporal dynamics of land use and its main drivers.	largely explains this increase. 181.95 km² of forest was lost, largely due to the expansion of cocoa production, although 180.50 km² of cultivated land was recovered as forest. The accuracy of the classifications was high, with values of 87.33% in 1986 and 91.33% in 2011.
Effects of Tree-crop Farming on Land-cover Transitions in a Mosaic Landscape in the Eastern Region of Ghana	[19]	The study analyses land cover changes in a semi-deciduous forest in Ghana using Landsat imagery from 1986 to 2015. One hundred and fifty-eight images were downloaded, from which those from 1986 and 2015 were selected after filtering for quality. Since there were no historical maps, information on landscape composition was obtained through interviews. Fifty-nine reference polygons were collected for 1986 and 908 for 2015, and various classification techniques were used, assessing accuracy with a change detection matrix.	The overall accuracies of the land cover maps for 1986 and 2015 were 91.2% and 78.8%, respectively, although the area estimates reduced these accuracies by about 6%. The accuracy of the 1986 map was better than that of the 2015 map. Forest and food crop land cover decreased by 11.9%, with an annual rate of change of 1.84% for forest and 1.75% for food crop land. On the other hand, oil palm experienced the largest increase in land cover at 11.2%, followed by cocoa at 8.9%. The annual changes for oil palm and cocoa were 1.93% and 1.06%, respectively.
Detecting cocoa plantations in Côte d'Ivoire and Ghana and their implications on protected areas	[20]	The study used 2019 Sentinel-1 and Sentinel-2 imagery in Google Earth Engine (GEE) to analyze land cover in Ghana. A total of 158 filtered images were downloaded to ensure quality and reduce cloud interference. 19,196 reference points were collected to validate the results, including 3,842 cocoa points collected in the field. The analysis included the application of pre-processing techniques to improve image quality, such as the calculation of the Normalized Difference Vegetation Index (NDVI) and Tasseled Cap Analysis, which considers brightness, greenness, and moisture. A Random Forest model was used for land use classification, and its accuracy was assessed through metrics such as overall accuracy and producer accuracy.	The study generated a thematic map of cocoa plantations using a Random Forest classifier, achieving an accuracy of 82.9% for the producer and 62.2% for the user. The area under cocoa cultivation is estimated at 3.69 Mha in Côte d'Ivoire and 2.15 Mha in Ghana. Approximately 1.18 Mha of the 5.8 Mha of plantations were found to be within protected areas (PAs), affecting 362 PAs, which represents about 70% in the studied region. Cocoa encroachment is more prevalent in PAs with a management category that allows human-nature interaction, compared to areas whose priority is biodiversity conservation. However, 40% of the PAs hosting cocoa plantations do not have information on their management category, showing a high percentage of cocoa encroachment.
Investigating relationships between Landsat-7 ETM+ data and spatial segregation of LULC types under shifting agriculture in southern Cameroon	[21]	The study was conducted in the tropical region of southern Cameroon, where shifting agriculture (slash-and-burn) causes forest conversion to land use diversity (LULC). Its objective was to analyze the relationships between LULC, Landsat-7 ETM+ imagery, and landscape structure. 171 crop plots representing eight LULC types were identified, and an ETM+ image obtained two months after field data collection was used. A maximum likelihood classifier (MLC) was used to classify LULC types, allowing the creation of a map with an accuracy of 81% after consolidating certain land use types, such as fallows and cocoa plantations. The landscape metrics obtained indicated a high level of patch diversity and connectivity, facilitating the simulation of predictive maps in areas with satellite imagery often covered by clouds.	The study examined Landsat ETM+ spectral responses to map land use and land cover (LULC) types in the rainforest of southern Cameroon. Although the spectral bands were able to discriminate between 50% and 60% of LULC types, crop fields, and short fallows showed more than 80% accuracy. Due to the difficulty in differentiating some plots, several LULC types were consolidated, allowing a map with 81% accuracy to be generated. The maximum likelihood classifier (MLC) was effective, and the landscape analysis showed high diversity and connectivity, useful for predictive mapping.
Cocoa crops are destroying the forest reserves of the classified forest of Haut-Sassandra (Ivory Coast)	[22]	The study was conducted in an area of 102,400 ha of forest surrounded by commercial crops such as coffee, cocoa, rubber, and cashews, as well as some areas of subsistence agriculture. Five satellite images from the years 1997, 2002, 2006, 2013, and 2015 were used, which were orthorectified and classified using a maximum likelihood algorithm. The land cover classes considered were: forest, bare soil, habitat, crop, and fallow. The most recent image was initially classified with 54 training zones validated by field visits. The results obtained were used to adjust the classifications of the previous images, and transition matrices were created to identify changes in the landscape over time.	The study showed an overall accuracy and kappa coefficient of over 80%. An increase in crop and fallow area coverage was observed due to the reduction of forest areas. The largest disturbances identified were cocoa plantations, felling and burning of trees, and trees burned at the base. Approximately 95% of the disturbances were of human origin and 5% of natural origin. Classification accuracy decreased in more heterogeneous environments, due to the difficulty of capturing detail when units are smaller than a pixel. The highest accuracy was achieved in more homogeneous areas before the conflicts.

Table 2 presents the main findings of the thematic review associated with each of the 10 most relevant articles (*continue*)

Title	Reference	Methodology	Findings
Spatial and temporal dynamic of land-cover/land-use and carbon stocks in Eastern Cameroon: a case study of the teaching and research forest of the University of Dschang	[23]	The study was carried out in the teaching and research forest of Dschang University in Cameroon to analyze changes in land cover and use, as well as carbon stocks. Landsat satellite images (5TM from 1984, 7ETM+ from 2000 and 8OLI from 2016) were used, and processed with ENVI and ArcGIS software. Interviews, group discussions, and participatory mapping were used to identify human activities. A forest inventory was carried out using 12 km long transects to measure dendrometric parameters and classify land use types. Carbon stocks were estimated using allometric models based on non-destructive methods. Aboveground and belowground biomass were calculated and the data were analyzed to assess carbon stock dynamics and forest cover changes.	The study mapped land cover into four classes: bare soil and built-up area, dense forest, light forest, and savanna. Bare soil and built-up areas were grouped together due to the similar reflectance of thatched roofs and soil. The dense forest includes primary, secondary, and swamp forests, while the light forest is degraded, sometimes coinciding with cocoa plantations or farms. Savannas and croplands were also grouped together due to the same reflectance in satellite images. Between 1984 and 2016, forest cover decreased, with losses of 937 ha between 1984-2000 and 931 ha between 2000-2016, while savanna vegetation increased. The Kappa index and overall accuracy were above 80%, indicating a good representation of reality.
Delineation of Cocoa Agroforests Using Multiseason Sentinel-1 SAR Images: A Low Grey Level Range Reduces Uncertainties in GLCM Texture-Based Mapping	[24]	The study was conducted in the Bakoa landscape in the central region of Cameroon, covering 123.28 km² of bush savannah, subsistence agriculture, and cocoa agroforests. RapidEye optical imagery with 5-meter resolution and five spectral bands were used, creating a mosaic from four images obtained in the same period. Fifty Sentinel-1A dual-polarized (VV and VH) C-band radar (SAR) images were also used, which were pre-processed using SNAP to remove noise and calibrate radiometry. Field data on land cover and land use were collected between 2015 and 2017. Several vegetation indices such as NDVI and SAVI were calculated using Random Forest algorithms in R. For SAR images, gray-level co-occurrence matrix (GLCM) textures were analyzed in 5×5 windows, measuring features such as entropy and contrast at different orientations.	Random Forest (RF) classification models achieved accuracies above 70%, although with variations in classification error and sensitivity between different land cover classes. The most reliable models were RE1, GLI3 and GL3. The combination of polarization bands (VV and VH) exceeded the accuracy of their individual use. However, the inclusion of backscatter GLCM texture measures and optical vegetation indices did not improve classification. The RE1 model excelled in identifying areas without vegetation, while SAR imagery offered reliable results for distinguishing cover types such as savannas and cocoa agroforests. Although multispectral optical imaging showed better overall performance, it was less effective in discriminating between evergreen agroforests and transitional forests.
Change vector analysis to categorise land cover change processes using the tasselled cap as biophysical indicator	[7]	The study used bi-temporal Landsat images from 1987 and 2002, applying the Change Vector Analysis (CVA) technique to analyze the differences in tasseled cap trajectories (which measure brightness and greenness) between the two years. The images were geometrically and topographically corrected. The magnitudes and directions of changes in forest cover were calculated from the differences in brightness and greenness. Thresholds were established to classify the changes into three intensity categories: low, medium, and high. Finally, the directions of change were identified and classified into 13 different categories of forest cover modification.	The results showed that the majority of the studied area experienced some type of change, with 76.75% gaining biomass and 21.7% losing it. The overall accuracy of the analysis was 70%. Areas of biomass loss and deforestation were detected mainly in areas close to villages or along main roads, while areas of forest regeneration were mainly located adjacent to these deforested areas. The technique allowed the identification of areas of positive and negative vegetation change, although the lack of complete historical data limited the validation of these results.
Regional land cover mapping in the humid tropics using combined optical and SAR satellite data—a case study from Central Sulawesi, Indonesia	[25]	The study was conducted in Central Sulawesi region, Indonesia, using Landsat-ETM+ and Envisat-ASAR satellite data to classify land use and land cover in a tropical environment. It focused on identifying intensive agricultural systems, such as cocoa plantations and rice crops, and on differentiating cultivated from forested areas. A multitemporal approach was used with synthetic aperture radar (SAR) data and the effectiveness of different polarization modes (co-polarization and cross-polarization) was evaluated to improve classification accuracy. SAR data were preprocessed to correct geometric and radiometric errors, and filters were applied to reduce noise. Indices and statistics were calculated to facilitate the separation of land use classes.	The study analyzed land cover classification in Central Sulawesi, Indonesia, using multitemporal synthetic aperture radar (SAR) and Landsat satellite data. Co-polarized SAR data achieved an accuracy of 69% with a Kappa index of 0.58, while cross-polarized data had a lower accuracy of 54% and a Kappa index of 0.40. The combination of multitemporal data and SAR textures achieved an accuracy of 68% (Kappa index of 0.57). Among the Landsat data, the 2004 data, with SLC-off, achieved an accuracy of 73% (Kappa index of 0.63), and the 2002 data showed the best overall accuracy, with 85% and a Kappa index of 0.79. The combination of Landsat and co-polarized SAR data resulted in the highest overall accuracy, reaching 89% (Kappa index of 0.85). These results highlight the effectiveness of

Table 2 presents the main findings of the thematic review associated with each of the 10 most relevant articles (*continue*)

Title	Reference	Methodology	Findings
		The classification was performed with an object-level nearest neighbor classifier, suitable for land cover types with heterogeneous spectral characteristics, such as rice fields. Various measures and indices, including the Normalized Polarimetric Difference Index and the Jeffries-Matusita index, were used to assess statistical separability.	combining optical and radar data to improve land cover classification in tropical environments, with the 2002 Landsat data being the most effective due to its high quality and lower cloud interference.

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