Integrated agronomic practices to improve cocoa (*Theobroma cacao* L.) productivity: A systematic review

Prácticas agronómicas integradas para mejorar la productividad de cacao (*Theobroma cacao* L.): una revisión sistemática

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ABSTRACT

Cacao (*Theobroma cacao* L.) cultivation is strategic for sustainable rural development in the tropics; however, yields remain low due to inadequate agronomic practices. This systematic review aims to identify agronomic management practices that increase cocoa crop yield by conducting a systematic search of Scopus following the PRISMA methodology. A total of 134 original scientific articles were selected from 2015 to 2025. Their data were analyzed using bibliometric tools such as R-Bibliometrix and VOSviewer, enabling identification of trends, key authors, and the frequency of agronomic practices. Approximately 12 key agronomic practices were identified, with the most relevant and widely studied being soil amendment, fertilization, agroforestry systems, pruning, irrigation systems, and phytosanitary control, implemented throughout the production cycle, from the nursery stage to the crop production phase. Limitations were identified, including the lack of long-term trials and the limited availability of specific data for local edaphoclimatic conditions, highlighting the need to strengthen applied research. This review demonstrates that when agronomic practices are employed in an integrated manner, they are essential for enhancing sustainability and productivity by more than 40%. Several challenges are addressed in implementing adequate agronomic practices for the cocoa crop in Colombia.

Keywords: mineral nutrition, ecophysiology, agroforestry, ecological stability.

RESUMEN

El cultivo de cacao (*Theobroma cacao* L.) es estratégico para el desarrollo rural sostenible en los trópicos, pero su rendimiento continúa siendo bajo debido a prácticas agronómicas inadecuadas. Esta revisión sistemática tiene como objetivo identificar las prácticas de manejo agronómico que han demostrado aumentar el rendimiento del cultivo de cacao, mediante una búsqueda sistemática en Scopus siguiendo la metodología PRISMA. Se seleccionaron 134 artículos científicos originales publicados entre 2015 y 2025, cuyos datos fueron procesados mediante herramientas de análisis bibliométrico con R-Bibliometrix y VOSviewer, lo que permitió identificar tendencias, autores clave y frecuencia de prácticas agronómicas. Se identificaron aproximadamente 12 prácticas agronómicas clave, siendo las más relevantes e investigadas: enmienda, fertilización, sistemas agroforestales, podas, sistemas de riego y control fitosanitario, implementadas a lo largo del ciclo productivo, desde la etapa de vivero hasta la fase de producción del cultivo. Se identificaron limitaciones asociadas a la falta de ensayos de largo plazo y la escasa disponibilidad de datos específicos para las condiciones edafoclimáticas locales, lo que resalta la necesidad de fortalecer la investigación aplicada. Esta revisión demuestra que las prácticas agronómicas, al ser implementadas de forma integrada, son esenciales para incrementar la sostenibilidad y la productividad en más del 40% en el cultivo del cacao. Se abordan varios desafíos relacionados con la implementación de prácticas agronómicas adecuadas para el cultivo de cacao en Colombia.

Palabras clave: nutrición mineral, ecofisiología, agroforestería, estabilidad ecológica.

Introduction

Global importance of the cocoa crop

Cocoa (*Theobroma cacao* L.) is native to the tropical rainforests of South America (Motamayor *et al.,* 2002), with production concentrated in Africa and Latin America; specifically, in West Africa, where Côte d'Ivoire and Ghana are the largest cocoa producers (Melo, 2025). In Latin America, Ecuador led annual production with 337,149 t of dry cocoa beans, followed by Brazil with 273,873 t (Espinosa, 2024). Colombia ranked fifth among large-scale producers with 73,678 t in 2024 (Fedecacao, 2025). The product has reached record prices worldwide in recent years; in 2022, the international price of dry cocoa beans averaged 2,300

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USD per t, while in 2024 it exceeded 10,000 USD (ICCO, 2025). This price increase is driven by a global deficit because of changing climatic conditions, aging plantations, and diseases that affected crops in West Africa, along with higher international demand (Kehinde & Tijani, 2021). The production of this crop is fundamental to the livelihoods of small-scale cocoa farmers, as it can contribute to household income and generate rural employment. However, it does not always guarantee stable and profitable income. In West Africa, most small producers do not achieve a living income (van Vliet *et al*., 2021).

In contrast, in Colombia, profitability varies with crop yield and crop productivity (Charry *et al*., 2025). In the Colombian context, cocoa has played a key role in sustainable rural development initiatives, in the transition toward legal crops through crop-substitution programs, and in the strengthening of the agricultural sector (MADR, 2020). However, this transition faces various challenges that limit its impact and effectiveness, including low productivity, poorly coordinated technical assistance, restricted market access, and lack of post-harvest infrastructure, as well as institutional discontinuity and the absence of sustainable incentives (Gil *et al*., 2023).

Knowledge gaps

A cocoa crop can be established in monocropping systems, where plants are exposed to direct sunlight, leading to a greater dependence on nutritional and phytosanitary inputs, increasing thermal and water stress, or in agroforestry systems with moderate shade, which optimize the microclimate without generating excessive humidity (Asman *et al*., 2024; Kouassi *et al*., 2024; Mensah *et al*., 2023). These agroforestry systems combine permanent and temporary shade with forest species and short-cycle or transitional crops such as plantain, maize, or cassava (Jagoret *et al*., 2017). This sustainable system protects young plants, contributes to soil conservation, enhances biodiversity, and generates additional income for farmers (Abdulai *et al.,* 2017). The implementation of agroforestry systems in cocoa cultivation improves sustainability by providing benefits such as carbon sequestration and climate change adaptation, surpassing monocultures in these aspects (Niether *et al.,* 2020).

Climate change severely impacts agroforestry systems by increasing the susceptibility of plantations to pests and diseases, thereby compromising the stability of the agroecosystem (Sousa *et al.,* 2019). West Africa is currently experiencing agricultural production losses, directly affecting food security in the region (Trisos *et al.,* 2023). In this context, cocoa production is at risk, as rising temperatures and precipitation are creating a favorable environment for the spread of fungal diseases (Bomdzele & Molua, 2023). Black pod disease, caused by *Phytophthora megakarya*, restricts production and deteriorates bean quality, directly affecting crop yield (Adeniran *et al.,* 2023). Its effective control requires agronomic practices including the removal of infected pods, fungicide application, and crop management through shade regulation and sanitary pruning; these strategies reduce disease incidence, improve yield, and optimize production (Adeniran *et al.,* 2024).

Objective and research question

Although various studies describe the benefits of agronomic practices for increasing cocoa yield, the information is scattered and often specific to particular conditions, which hampers a comprehensive understanding. Therefore, the aim of this review was to compile and systematically analyze information on actual management practices that enhance cocoa yield.

Materials and methods

Literature search

A systematic search was conducted in the SCOPUS database, following the PICO methodology (Population, Intervention, Comparator, and Outcome) (Eriksen & Frandsen, 2018) to structure the research question: *Which agronomic practices increase cocoa yield?* The review was carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page *et al.,* 2021), enabling a bibliometric analysis that identified the most studied strategies and their effectiveness in improving crop productivity.

A systematic search was carried out between March and April 2025, selecting articles published between 2015 and 2025. Keywords were combined using Boolean operators to optimize the accuracy of the results obtained. Some of the combinations used were: Article title: "*Theobroma cacao*" OR "cacao" OR "cacao cultivation" OR "cacao plantations" OR "agronomic practices cacao" OR "agricultural practices cacao" OR "sustainable practices cacao" OR "agronomic practices cocoa" AND title, abstract, and keywords: "cacao agronomic practices" OR "crop management" OR "cacao agricultural practices" OR "sustainable practices" OR "field experiment" OR "cacao pruning" OR "shade regulation" OR "cacao renewal" OR "cacao rehabilitation" OR "agroforestry systems in cacao" OR "cacao agroforestry"

OR all fields: "rehabilitation and renovation in cocoa" OR "cacao rehabilitation and renovation" OR "cacao pruning methods" OR "cacao fertilization" OR "amendment" OR "cacao propagation" OR "cacao irrigation" OR "weed control" OR "cacao phytosanitary control" OR "cacao hybrid varieties" OR "grafting techniques in cacao" AND all fields: "cacao productivity" OR "production efficiency" OR "cocoa production" OR "cacao yield" OR "cacao yield improvement" OR "sustainable" AND NOT all fields: "cadmium" OR "sensory" OR "husk" OR "flavonoids" OR "climate change" OR "shell".

Inclusion and exclusion criteria

The Scopus search yielded 412 articles, which underwent initial screening based on title, abstract, and keywords, resulting in the exclusion of 245 articles. From the 167 potentially relevant articles, original research publications that addressed one or more agronomic interventions to increase cocoa yield and quality were selected. Review articles, papers focusing solely on chocolate quality, and papers on socio-economic aspects without reference to crop agronomic management, or without agronomic data, were excluded. The final database consisted of 134 articles, containing variables such as year of publication, title, abstract, authors and co-authors, institutions, and countries of affiliation.

Bibliometric analysis

The records from the Scopus database were exported in BibTeX format, which is a text file format. Subsequently, a network analysis was conducted to identify the leading countries in cocoa agronomic practices and to uncover trends based on the frequency of terms in titles and abstracts. For this analysis, a bibliometric evaluation was conducted using the Bibliometrix package in R (version 4.3.3) and the VOSviewer software (version 1.6.20).

Results

Description of the selection process (PRISMA)

The selection process is summarized in Figure 1 using the PRISMA methodology. After the application of inclusion and exclusion criteria, 134 scientific articles were retained for the final analysis. This collection of studies identified 12 distinct agronomic practices, totaling 284 citations across the selected articles. This number exceeds the total publications because several articles addressed more than one practice. The most frequent practices were: varieties (n = 11), irrigation (n = 9), weed control (n = 16), propagation (n = 5), soil amendment (n = 28), phytosanitary control (n = 4), agroforestry (n = 64), fertilization (n = 24), rehabilitation (n = 1), grafting (n = 4), general agronomic practices (n = 76), pruning (n = 21), and shade regulation (n = 21). These categories represent the most frequent and relevant practices in the analyzed scientific articles.

Bibliometric search analysis and its impact on research

Annual scientific production

During the period from 2015 to 2025, the research on the implementation of agronomic practices to improve cocoa yield resulted in 134 publications (Fig. 2A). The annual growth rate of the selected publications was 1.34. The scientific output showed two growth peaks between 2016 and 2018, followed by a decline in 2019, probably due to external factors such as the COVID-19 pandemic. In 2021, the peak coincided with the most significant number of publications. This growth rate appears to decline starting in 2024, possibly because research interest in cocoa over the last two years has focused more on the impact of climate change on production in central African cocoa-producing countries (Asante *et al.,* 2025).

Co-occurrence analysis among authors, keywords, and countries

The relationships among the most influential authors, predominant keywords, and the countries involved are shown in Figure 2B. The lines connecting these elements reflect the frequency with which they co-occur in the analyzed articles, highlighting the main research areas and the geographic contributions to the cocoa crop.

Keyword analysis

Figures 2C and 2D present the co-occurrence and temporal evolution analyses of keywords extracted from the 134 selected scientific articles, highlighting the importance of agronomic practices applied to cocoa cultivation between 2015 and 2025. Terms such as "agroforestry" and "soil management" appear frequently and are highly connected, reflecting their central role in scientific research. These keywords are closely related to the significance of agronomic practices, as they represent key strategies to improve crop productivity, sustainability, and yield.

In this part of the analysis, we observed that terms such as "agroforestry" and "soil management" appeared frequently, indicating that cocoa research has focused on managing the edaphic environment and integrating cocoa with agroforestry systems. These approaches not only enhance productivity but also help conserve natural resources. Furthermore, Figure 2D highlights the temporal evolution of these topics, showing an increasing interest in concepts such as "soil fertility" and "species diversity" in recent years.

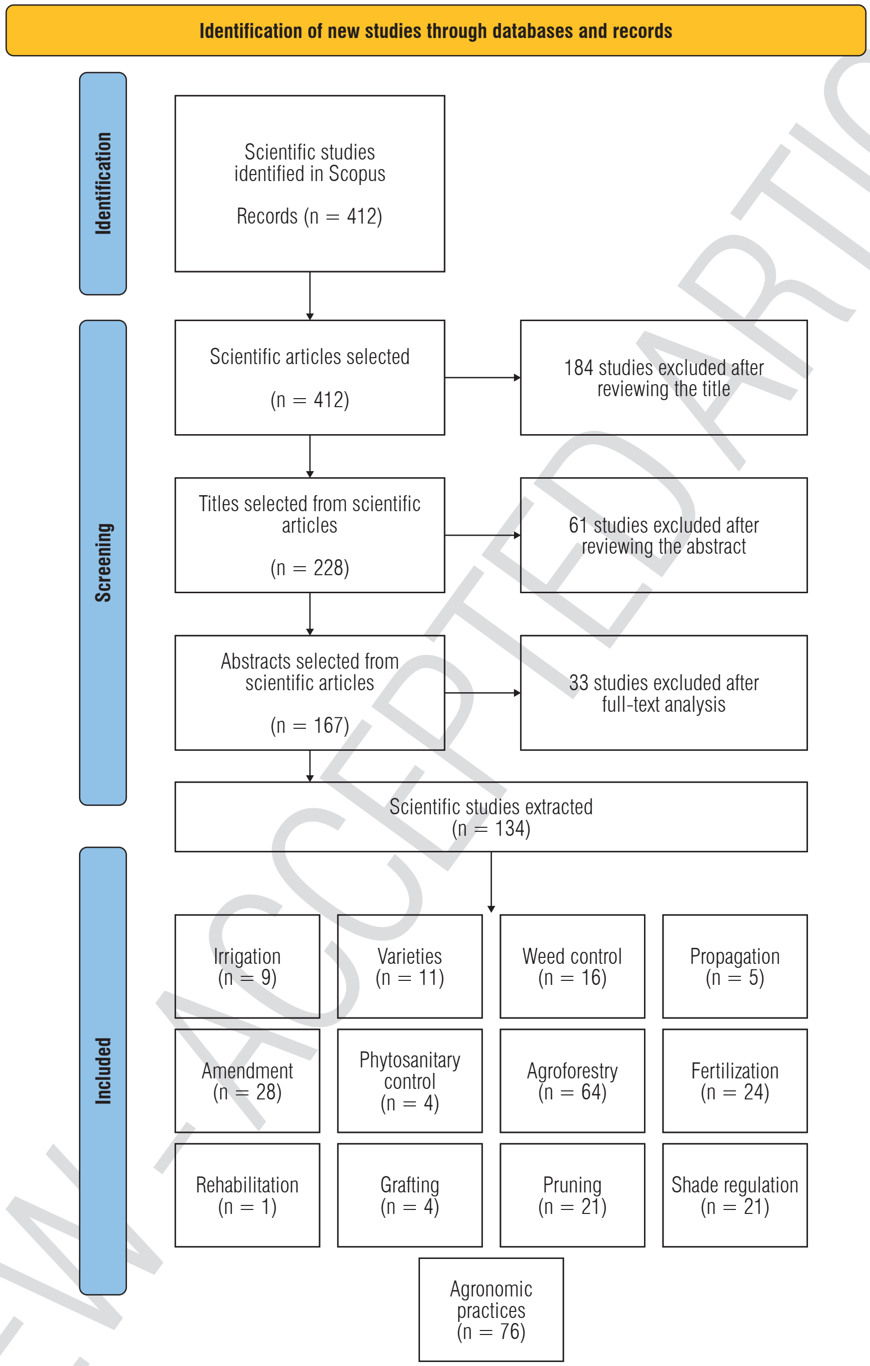

FIGURE 1. Flow diagram of the review and selection process for the identification and inclusion of articles in the systematic review (PRISMA diagram).

Most cited authors

Table 1 presents the most cited authors in studies on cocoa agronomic practices, based on the search in the Scopus database. Among them, according to our search, researchers Laura Armengot, Monika Schneider, and Joachim Milz stand out. Their studies are widely referenced for their focus on sustainable agroforestry systems.

The high citation of these studies highlights the relevance of topics such as integrated management, soil conservation, and functional biodiversity. The scientific contributions of authors such as Arévalo-Gardini and Pierre Gras are also noteworthy, as they delve into soil fertility and biological control. Taken together, these authors help to consolidate a comprehensive and sustainable perspective on cocoa production.

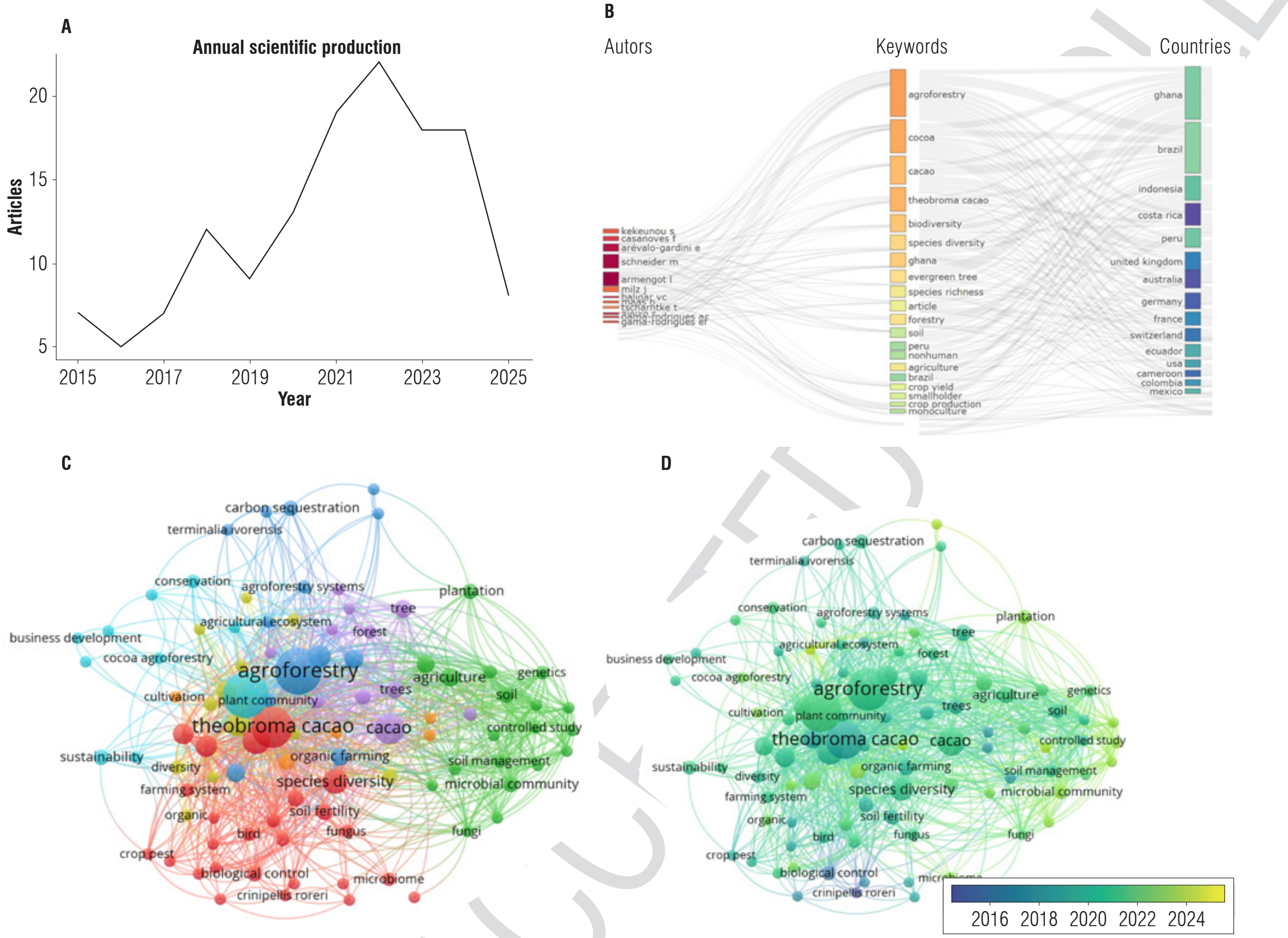

FIGURE 2. Bibliometric analysis of agronomic practices in cocoa between 2015 and 2025: Annual scientific production, co-occurrence of authors, keywords, and thematic evolution.

TABLE 1. Most cited articles on agronomic practices in the cocoa crop published in 2015-2025.

Authors	Title	Total citations	Abstract	Keywords
Armengot *et al.* (2016)	Cocoa agroforestry systems have a higher return on labor compared to full-sun monocultures	87	This study compares cocoa agroforestry systems and monocultures. It concludes that the former yields higher returns per unit of labor, promoting economic sustainability.	Agroforestry, cocoa, labor efficiency, profitability, sustainable farming
Grass *et al.* (2016)	Ants, birds, and bats affect crop yield along shade gradients in tropical agroforestry systems with cocoa	72	This research shows how functional biodiversity (ants, birds, and bats) positively influences cocoa yield along shade gradients.	Biodiversity, cocoa, natural enemies, shade gradient, agroecology
Arévalo-Gardini *et al.* (2015)	Changes in soil physical and chemical properties in long-term improved natural and traditional agroforestry management systems of cocoa genotypes in the Peruvian Amazon	70	The study demonstrates that long-term agroforestry practices improve soil structure and fertility, benefiting the development of cocoa genotypes in the Amazon.	Soil quality, cocoa genotypes, agroforestry management, Amazon, long-term impact
Armengot *et al.* (2020)	Cocoa agroforestry systems do not increase pest and disease incidence compared with monocultures under good cultural management practices	63	Under good cultural practices, agroforestry systems do not exhibit higher pest or disease incidence than monocultures, which contradicts previous assumptions.	Pest management, diseases, cocoa, cultural practices, and agroforestry
Kotowska *et al.* (2015)	Patterns in hydraulic architecture from roots to branches in six tropical tree species from cocoa agroforestry and their relation to wood density and stem growth	62	Hydraulic traits are evaluated in cocoa agroforestry systems, finding a relationship between water transport efficiency, wood density, and growth.	Shade tree, hydraulic conductivity, cocoa agroforestry, tropical trees, water transport, wood density

Technical support programs and good agronomic practices in Colombia

The actual annual cocoa bean yield in Colombia is estimated at around 450 kg ha^{-1}, which is well below the genetic potential of the cocoa accessions available in the country, which could exceed 2 t ha^{-1} under optimal conditions (Fedecacao, 2025). The causes of low productivity include inadequate agronomic practices, such as improper fertilization, lack of pruning, aging plantations over 20 to 30 years with declining productive capacity, genetic material susceptible to pests, planting densities above 1,200 plants per ha, the absence of an appropriate agroforestry system, or excessive shade, all of which favor the incidence of diseases such as moniliasis (*Moniliophthora roreri*) and others. The lack of proper agronomic practices can lead to excessive competition of plants for light, water, and mineral nutrients, negatively affecting plant development and crop productivity (Jaimes Suárez *et al.,* 2022).

In Colombia, organizations such as Fedecacao, Agrosavia, and the Compañía Nacional de Chocolates (CNCh) have led programs promoting the adoption of Good Agricultural Practices (GAP) in cocoa, training producers in pruning, grafting, fertilization, and post-harvest management (AGROSAVIA, 2024). CNCh has promoted the renewal of aging plantations through new plantings via initiatives such as Viveros para la Paz (2018) and PLANTAR (2024), with an investment of 1.5 billion Colombian peso aimed at producing 10 million seedlings over five years. These nurseries, registered with the Colombian Agricultural Institute (ICA), ensure the supply of high-quality planting material; between 2018 and 2023, CNCh distributed approximately 3.9 million seedlings to partner producers. Within the framework of these programs, CNCh recommends and distributes various high-yield regionally adapted clones, including CCN-51, FEAR-5, FSV-41, ICS-95, FEC-2, CNH-12, and CNH-13, which have been previously evaluated across different regions of the country and show good agronomic performance, productivity, and disease tolerance. In addition, CNCh supports rural youth and women through programs such as ATENEA and Generación Theobroma (GenThe), which promote agricultural innovation and generational renewal in the sector (Grupo Nutresa, 2024).

In terms of international cooperation, the AGROEMPREND Cacao project, implemented by SOCODEVI with funding from the Government of Canada, has benefited 5,000 families with technical assistance, implementing agronomic practices such as fertilization, pruning, and plantation renewal, thereby improving productivity in regions such as Meta and César (SOCODEVI, 2021). USAID, through the Mi Tierra Próspera program, which operates across various value chains, including cocoa, has supported land titling and infrastructure development and has provided technical assistance and small-scale irrigation systems in certain areas. Additionally, the USAID Sustainable Agriculture program participates in technical roundtables of public-private partnerships. It is benefiting over 900 families across 7 municipalities through the Development Programs with Territorial Focus (PDET) through training focused on regenerative agriculture (ADR, 2025).

The German cooperation agency GIZ has promoted sustainable practices, women's inclusion, and the strengthening of biofactories. The Colombian Cacao and Complementary Crops for Development Project (C4D) is an initiative funded by the USDA and implemented by Partners of the Americas in 14 Colombian departments. Its goal is to increase cocoa productivity, diversify crops, improve the incomes of small producers, and strengthen their associations. C4D has benefited more than 5,000 cocoa growers, promoted climate insurance schemes such as Cacao Seguro, and encouraged sustainable practices, including agroforestry, renewal of aging plantations, and post-harvest management, positioning Colombian cocoa as a driver of sustainable rural development (C4D, 2023).

Among the various initiatives implemented in Colombia, C4D stands out as one of the most impactful and comprehensive programs, thanks to its clear objective of significantly increasing productivity while simultaneously promoting key success factors. Its integrated approach and broad territorial reach make it a benchmark for rural development efforts along the country's cocoa value chain.

Identification of agronomic practices that increase cocoa yield

Organic amendments and soil correction

Cocoa is a crop that heavily depends on soil conditions. The bibliometric search revealed recent studies confirming that the application of organic amendments such as compost increases soil organic matter content, thereby improving cation exchange capacity (CEC) and water retention (Murillo-Montoya *et al.,* 2020). The application of lime and organic amendments in acid soils is a fundamental practice for improving cocoa productivity, as lime neutralizes soil acidity, reduces aluminum toxicity, and increases the availability of essential nutrients such as phosphorus, calcium, and magnesium. In tropical regions, where cocoa is grown in acidic soils with a pH < 5.5, this directly affects root development and fertilization efficiency (Arévalo-Hernández *et al.*, 2022). For example, the application of dolomite lime, which provides calcium and magnesium, raises the pH to an optimal range between 6.0 and 6.6, improving the absorption of nitrogen and potassium, which could provide an increase in crop yield of up to 25% compared to uncorrected soils (Rosas-Patiño *et al.,* 2019).

The doses of lime are of key importance, as its excesses can increase soil pH and cause deficiencies of metal micronutrients zinc, copper, manganese, and iron; that is why it is recommended to carry out physicochemical soil analyses before the applications with amendments, to determine the specific required dose of lime; this practice, integrated with a balanced fertilization, has been shown to increase cocoa production (Arévalo-Hernández *et al.,* 2022).

In conclusion, liming and the application of organic amendments are essential agronomic practices for increasing cocoa yield, provided they are applied on time and based on soil physicochemical analysis.

Fertilization

According to a bibliometric search, balanced mineral nutrition is essential to maximize cocoa yield, as nutritional requirements vary considerably across the crop's phenological stages. In this regard, the analyzed research indicates that, during the nursery stage, phosphorus is fundamental for root development. At the same time, nitrogen promotes leaf growth. In the production stage, potassium is key for fruit filling and disease resistance (Snoeck *et al.,* 2016). Additionally, micronutrients such as zinc and boron play essential roles in physiological processes, and deficiencies of these micronutrients can reduce cocoa yield and productivity (Arévalo-Hernández *et al.,* 2022).

The nutrient requirements of cocoa vary with phenological stage. In the nursery (0 to 6 months), seedlings demand low nutrient doses, between 2.4 kg ha^{-1} of nitrogen, 0.8 kg ha^{-1} of phosphorus, 2.4 kg ha^{-1} of potassium, 2.3 kg ha^{-1} of calcium, and 1.1 kg ha^{-1} of magnesium (Quiñones-Cabezas *et al.*, 2024). Although in the nursery cocoa seedlings are planted individually in bags, these values were taken from scientific publications that standardize nutrient demand in kg ha^{-1} to maintain consistency and comparability across the crop's different phenological stages. During the growth stage (1 to 3 years after establishment in the field), requirements increase to 80-150 kg ha^{-1} of nitrogen, 14 kg ha^{-1} of phosphorus, 150 kg ha^{-1} of potassium, and 80-120 kg ha^{-1} of calcium (Leiva-Rojas & Ramírez-Pisco, 2017). In the productive phase (after 3 years of establishment in the field), 150 to 220 kg ha^{-1} of nitrogen, 20 to 23 kg ha^{-1} of phosphorus, 250 to 320 kg ha^{-1} of potassium, and 100 to 140 kg ha^{-1} of calcium are required (Furcal-Beriguete, 2017), reaching maximum nutritional demand in plantations older than five years, with up to 440 kg ha^{-1} of nitrogen and 630 kg ha^{-1} of potassium (Carmona-Rojas *et al.*, 2022; González, 2020). These values are consistent with reports highlighting the importance of balanced fertilization to replenish nutrients extracted during harvest and maximize cocoa productivity (Sitohang *et al.*, 2019).

Information from various studies indicates that mineral elements such as nitrogen, phosphorus, and magnesium are mainly concentrated in the beans. At the same time, potassium accumulates primarily in the pod husk, contributing to fruit filling and solute transport into the fruits (Rosas-Patiño *et al.,* 2021).

Nitrogen exhibits high uptake and is fundamental during vegetative growth and flowering, as it increases aboveground biomass and stimulates the formation of reproductive structures (Capa-Morocho *et al.,* 2022). Phosphorus shows a moderate but steady absorption and is key in the development of the root system during the first months of growth, facilitating the efficient uptake of water and other nutrients. In the reproductive stage, phosphorus is essential for fruit set and development, as it promotes the formation of floral structures (Puentes-Páramo *et al.,* 2014).

The plants exhibit a high demand for potassium during fruit formation, which is associated with fruit set, greater pod filling, and improved yield in cocoa (Weinstein *et al.,* 2024). Magnesium and calcium exhibit moderate and relatively stable absorption rates by the roots throughout the cocoa growth cycle; magnesium participates in chlorophyll synthesis and the transport of photoassimilates (Ishfaq *et al.,* 2022), while calcium is essential for the rigidity and stability of cocoa fruit tissues, helping to prevent malformations and premature drop; therefore, proper fertilization management is key to maximizing cocoa productivity and quality (Avianto, 2025; Wdowiak *et al.,* 2024). Meanwhile, the micronutrients manganese, zinc, and boron are essential during pod set and development, as their deficiency can cause pod deformities or asymmetries and poor seed formation; their proper application improves both quality and yield (Jegadeeswari *et al.,* 2024; Sousa Filho *et al.,* 2021).

This information is fundamental for establishing precision fertilization programs. Instead of relying on applications based on traditional criteria without prior diagnosis. Data on mineral absorption indicate that the nutrient supply should be synchronized with the phases of highest demand

(Álvarez-Carrillo *et al.,* 2015; Carmona-Rojas *et al.,* 2022; León-Moreno *et al.,* 2019). This strategy not only optimizes nutrient use efficiency but also prevents fertilizer waste and maximizes the physiological effect on productivity. Proper fertilization, based on the nutritional requirements for each phenological stage and supported by a physico-chemical soil analysis, not only significantly increases cocoa productivity but also strengthens the plants against biotic and abiotic stress. These results have also been confirmed in various recent studies. The strategic combination of organic sources with chemical fertilizers is a sustainable practice to optimize cocoa production (Ali *et al*., 2018).

Pruning management and its impact on productivity

Pruning is an agronomic practice that should not be overlooked in cocoa cultivation, as it has proven to be essential for increasing productivity, improving bean quality, and extending the productive lifespan of cocoa plantations. Recent studies confirm that proper technical pruning can increase yields by 30% compared to unpruned plantations, mainly by optimizing the distribution of photosynthates to pod production and reducing the incidence of diseases (López-Báez *et al.,* 2025).

There are different types of pruning, where formation pruning must be carried out during the first three years and is essential to define the architecture of the plant; it is recommended to leave between three and five main branches well distributed, to facilitate the interception of light throughout the canopy and internal aeration, a factor that reduces by 50% the incidence of diseases such as moniliasis (*Moniliophthora roreri*) (Djuideu *et al.,* 2021).

In productive cocoa plantations (with approximately 5 or more years since establishment in the field), maintenance pruning is carried out annually, this practice includes the elimination of suckers, diseased and dead branches, and it has been shown that it increases photosynthetic efficiency by redirecting assimilates and nutrients toward actively photosynthetic leaves and developing fruits; this practice, when combined with a balanced fertilization, increases the number of pods per tree (Esche *et al.,* 2023).

Rehabilitation pruning in aging or abandoned plantations, which involves cutting primary branches at 1.5 to 2 m in height, has made it possible to restore productivity to 800 kg ha^{-1} year^{-1}, compared to 200 kg ha^{-1} year^{-1} in unrehabilitated plants, due to the growth stimulation of new and productive shoots (Somarriba *et al.,* 2021).

In plantations over 20 years old in the Caribbean region of Colombia (Zona Bananera, Magdalena Department, and Valledupar, César Department), rehabilitation pruning, along with side grafting and renewal of planting material, resulted in significantly higher yields compared to non-intervened plots. In Colombia, it has proven to be a successful agronomic practice, increasing yield, improving fruit quality, and reducing diseases, making it a key tool for the sustainability and productivity of the crop (Yacomelo-Hernández *et al.,* 2021).

When this cultural management is carried out according to technical criteria, it increases cocoa yield. Also, it strengthens crop health by reducing favorable environments for pathogens. Its integration with other management practices (fertilization, agroforestry systems) is essential to achieving sustainable and highly productive cocoa cultivation. The bibliometric data indicate that pruning is fundamental to overcoming the traditional productivity limits in cocoa.

Implementation of agroforestry systems

Agroforestry systems have been established as a key strategy to increase cocoa production while simultaneously preserving essential ecosystem functions. Recent studies show that cocoa cultivated under agroforestry systems with moderate shade (30-35%) can yield 1,500 kg ha^{-1} year^{-1}, surpassing monocultures under the same edaphoclimatic conditions by 25% (Somarriba *et al.,* 2021). This productive advantage is mainly due to improved microclimatic conditions, which reduce thermal and water stress, and to the constant supply of organic matter that maintains soil fertility (Djuideu *et al.,* 2021).

The appropriate selection of companion tree species is fundamental to maximizing the benefits. Leguminous species such as *Inga* spp. or *Erythrina* spp., when managed at densities of 50 to 60 trees per hectare, not only fix atmospheric nitrogen but also improve water infiltration and reduce soil erosion by 60% compared to systems without tree cover (Borden *et al.,* 2019).

From a phytosanitary perspective, agroforestry systems reduce the incidence of diseases such as moniliasis and witches' broom because plant diversity disrupts pathogen cycles and promotes natural biological control (Arévalo-Gardini *et al.,* 2020).

In Colombia, the implementation of cocoa agroforestry systems recurrently integrates musaceous plants such as plantain or banana (*Musa* sp.); native timber trees such as abarco (*Cariniana pyriformis* Miers) and cedro (*Cedrela odorata* L.); fruit trees such as guayavo (*Psidium guajava* L.) and aguacate (*Persea americana* Mill.); and leguminous plants such as mataratón (*Gliricidia sepium* (Jacq.) Kunth ex Walp.) and leucaena (*Leucaena leucocephala* (Lam.) de Wit) (Hernández-Nuñez *et al.,* 2024). The data of the scientific research from the last 10 years demonstrate that the implementation of agroforestry systems improves yields through the optimization of resources (light, water, and mineral nutrients) and strengthens crop resilience to both biotic stress (reduction of pest and disease incidence) and abiotic stress (mitigation of temperature extremes and water deficit), contributing to a more stable and sustainable production over time.

Studies conducted in the Ecuadorian Amazon confirm these findings, showing that cocoa cultivated under agroforestry systems yields higher yields, better water balance, and lower disease incidence than conventional systems under full sun exposure (Tinoco-Jaramillo *et al.,* 2024).

Integrated pest management (IPM)

Integrated Pest Management (IPM) is a fundamental strategy for ensuring the productivity and sustainability of the cocoa crops. Recent studies show that effective implementation of IPM practices can increase yields by significantly reducing losses caused by pathogens and insect pests (Armengot *et al.,* 2019). The combination of biological, cultural, and rational chemical controls has shown particular effectiveness against diseases such as moniliasis (*Moniliophthora roreri*) and witches' broom (*Moniliophthora perniciosa*), especially when sanitary pruning is applied promptly (Doe *et al.,* 2023).

Varietal resistance plays a very key role in pest management, where clones CCN-51 and ICS-95 have shown proven tolerance to diseases, requiring fewer fungicide applications while maintaining high production (Jaimez *et al*., 2022). However, according to Vera *et al.* (2024), this strategy must be complemented with periodic monitoring every 8 d to detect epidemic outbreaks early, allowing precise interventions that reduce control costs.

Integrated pest management increases cocoa productivity by effectively protecting against pests and diseases, improves profitability by reducing dependence on external chemical inputs for pest and disease control, while minimizing environmental impacts. A bibliometric analysis indicates that integrating comprehensive pest management strategies is a key element in the successful management of cocoa plantations.

Importance of seed selection and propagation practices in cocoa cultivation

Genetic selection and propagation methods are fundamental for establishing cocoa plantations with high productive potential. Studies show that the use of selected seeds from elite trees or mother trees of high production, which produce healthy pods, large beans and show tolerance to several pests and diseases, can increase future yields compared to non-selected material, due to the expression of superior characteristics in vigor, disease resistance and bean quality (Laliberté *et al.,* 2015; Padi & Ofori, 2016). Regarding propagation methods, grafting with clones has shown significant advantages over seed propagation, reducing the unproductive period from 3 years to 2 years and maintaining genetic uniformity in the plantations. Technical practices such as terminal bud grafting have reached success rates of 85-90% when performed on vigorous rootstocks of 3-4 months of age and where relative air humidity (80-85%) and air temperature (25-28°C) are controlled during the grafting process (Ali *et al.,* 2018).

The investment in selection and quality propagation is the basis for establishing productive and sustainable cocoa plantations, confirming that selecting genetic material can significantly increase productive yield; and these benefits are cumulative when combined with other agronomic practices. In Colombia, clones FEAR-5, FSV-41, ICS-1, ICS-95, FEC-2, FTA-2, LUKER 40, CNCH 12, CNCH 13, and CCN 51 stand out for their high production potential and are registered with the ICA, which ensures their quality and traceability as certified materials for commercial planting (Meza-Sepulveda *et al*., 2024; Rodriguez-Medina *et al*., 2019).

Irrigation practices

The implementation of irrigation systems in cocoa cultivation is a key strategy to increase and stabilize production, especially in regions with marked dry periods. The bibliometric search confirms that complementary irrigation during times of water deficit can increase yields compared to systems dependent exclusively on rainfall. This improvement is mainly due to the maintenance of soil moisture in the optimal range, which favors nutrient absorption and reduces physiological stress during critical phases such as flowering and fruit filling (Agele *et al.,* 2016).

Drip irrigation systems have shown efficiency in cocoa plantations, with water savings of 30-40% compared to traditional gravity methods, while at the same time increasing productivity to 1,200-1,500 kg ha^{-1} $year^{-1}$ under optimal conditions. Many experimental studies reveal that the irrigation frequency must be adjusted according to the soil texture to avoid waterlogging that favors root pathogens (Sujatha & Bhat, 2015).

In Colombia, a study conducted in the department of Cauca (2015-2016) showed that combining drip irrigation and pruning in six-year-old plants increased the number of fruits per tree and seed weight, improving productivity, bean quality, and phenological management efficiency. Moreover, this practice helped reduce pests and diseases, establishing itself as a viable alternative to increase cocoa yields and stability in the face of the country's variable conditions and climate change (Meneses-Buitrago *et al.*, 2019).

Irrigation could be an effective tool for improving cocoa yield, particularly in scenarios of climate variability. The data analyzed, supported by research over the past 10 years, shows that optimal implementation requires selecting the appropriate system based on local conditions, continuous monitoring of soil moisture, and adjusting schedules according to the phenological stage. This practice, when integrated with others such as fertilization and pruning, can significantly increase productivity.

Figure 3 integrates each of the main agronomic practices for cocoa cultivation and their benefits, showing that their implementation leads to visible improvements in crop condition. As more practices are incorporated, vigor, plant health, and yield increase, consolidating a more sustainable and efficient production system.

Conclusions

This systematic review identified a set of key agronomic practices that directly influence cocoa yield, quality, and sustainability of cocoa cultivation. Based on the bibliometric analysis, it was evident that cocoa productivity depends on appropriate agronomic management adjusted to the specific conditions of each producing region. The reviewed literature highlights that, in producing countries across Africa, Latin America, and Asia, the success of the crop and its yield is related to the timely and articulated implementation of agronomic management practices.

The implementation of agronomic practices such as balanced fertilization, agroforestry systems, pruning, irrigation, and integrated pest management directly affects

Agronomic practice	Associated benefit	Source
Seed selection and propagation of quality planting material.	Improves vigor, uniformity, and establishes a solid genetic base.	(Abdulai *et al.*, 2017; Laliberte *et al.*, 2015; Padi & Ofori, 2016).
Implementation of agroforestry systems.	Increases resilience to climate change and contributes to sustainability.	(Arévalo-Gardini *et al.*, 2020; Borden *et al.*, 2019; Djuideu *et al.*, 2021).
Installation of irrigation systems.	Optimizes water supply, especially during dry seasons.	(Agele *et al.*, 2016; Sujatha & Bhat, 2015).
Application of organic amendments and soil correction.	Improves soil structure and nutrient availability.	(Rosas-Patiño *et al.*, 2019; Rosas-Patiño *et al.*, 2021).
Balanced fertilization and nutrition.	Increases yield and quality of cocoa pods.	(Arévalo-Hernández *et al.*, 2022; Puentes-Páramo *et al.*, 2014; Puentes-Páramo *et al.*, 2016).
Pruning for formation, maintenance, and phytosanitary control.	Stimulates flowering, facilitates crop management, and reduces phytosanitary risks.	(Djuideu *et al.*, 2021; Esche *et al.*, 2023; López *et al.*, 2025; Somarriba *et al.*, 2021).
Integrated pest management.	Reduces losses from biotic damage and improves final production.	(Armengot *et al.*, 2019; Doe *et al.*, 2023, Vera-Velez *et al.*, 2024).
Without agronomic management	**Partial management (1–2 practices)**	**Integrated agronomic management**
		

FIGURE 3. Key agronomic practices in cocoa cultivation, associated benefits, and their impact on production.

growth and fruit filling. It can increase yield by up to 40% when applied correctly. This analysis highlights the importance of comprehensive agronomic management that spans from the nursery phase to the crop's productive stage.

In Colombia, it is recommended to strengthen the implementation of balanced fertilization, agroforestry systems, and pruning, given their fundamental role in increasing productivity and improving crop health. These practices may represent a promising line of research to deepen understanding of crop physiology. In general, the cocoa agronomic management must be understood and managed as an integrated system rather than a set of isolated practices, where proper planning, diagnosis, and technical management make it possible to improve the income of small producers, production efficiency, food security, and the sustainability of this crop according to the bibliometric analysis conducted.

Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

MCHB: conceptualization, writing – original draft, visualization, writing, and editing. HDRB: conceptualization, writing, and supervision editing. ZCCR: conceptualization, visualization, writing, and editing. All authors have read and approved the final version of the manuscript.

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