Nutrition in cacao (*Theobroma cacao* L.) crops: What determining factors should be considered?

Nutrición en los cultivos de cacao (*Theobroma cacao* L.): Que factores que deben ser considerados?

Laura Michell Carmona-Rojas *
Grupo de Biotecnología, Facultad de Ciencias Exactas y Naturales, Universidad de Antioquia,Medellín, Colombia

Edwin Antonio Gutiérrez-Rodríguez
Postdoctoral Associate at Tropical Research and Educational Center, University of Florida, EstadosUnidos

Ana María Henao-Ramírez
Grupo de Biotecnología, Facultad de Ciencias Exactas y Naturales, Universidad de Antioquia,Medellín, Colombia

Aura Inés Urrea-Trujillo
Grupo de Biotecnología, Facultad de Ciencias Exactas y Naturales, Universidad de Antioquia,Medellín, Colombia

Revista de la Facultad de Agronomía
Universidad Nacional de La Plata, Argentina
ISSN: 1669-9513
Periodicity: Semestral
vol. 121, (Num. Esp. 2), 2022
redaccion.revista@agro.unlp.edu.ar
Received: 31/07/2022
Accepted: 22/09/2022

URL: http://portal.amelica.org/ameli/journal/23/233546009/
DOI: https://doi.org/10.24215/16699513e101
Corresponding author: laura.carmona@udea.edu.co

Abstract

Cacao (*Theobroma cacao* L.) is an important commercial crop and agricultural commodity worldwide; for some Latin American countries, it is an essential part of export products. In Colombia, this crop has promising conditions to extend and strengthen this agriculture sector.However, their productivity is low under current agricultural practices, mainly due to insufficient modernization and inadequate or no management of their nutritional schemes. This publication reviewed the different findings currently in the scientific literature regarding the factors that determine the nutritional status of cacao plants, such as the function and distribution of minerals, nutritional efficiency, soil properties, establishment systems, organic and organic and inorganic sources examined. Additionally, it highlighted the importance of using and expanding diagnostic tools to determine nutritional needs and the design of effective programs according to the particular conditions of each region and the genotypes planted. This conceptual journey highlights the existing theoretical and experimental gap in the identification of the factors that determine the nutritional status of the plantations and their effect on the implementation of the fertilization programs used today. Information together provides elements to adequately address this agronomic practice and the economic impact on farmers and the cacao production chain.

Keywords: nutritional diagnosis, mineral distribution, essential elements, nutritional efficiency, chemical/organic fertilization.

Resumen

El cacao es un importante cultivo comercial y commodity agrícola a nivel mundial, para algunos países de Latinoamérica es parte importante de los productos de exportación. En Colombia este cultivo presenta condiciones promisorias para extender y fortalecer este sector de la agricultura. Sin embargo, bajo las prácticas agrícolas actuales sus productividades son bajas,debido principalmente a la insuficiente tecnificación, así como a un manejo inadecuado o nulode sus planes nutricionales. En esta publicación se revisaron los diferentes hallazgos encontrados en la literatura científica disponible a la fecha, respecto a los factores que determinan el estado nutricional de las plantas de cacao. Entre ellos se examinaron la funcióny distribución de los minerales, la eficiencia nutricional, las características fisicoquímicas del suelo, los aportes nutricionales de los sistemas agroforestales y de fuentes orgánicas e inorgánicas. Igualmente se resaltó la importancia de usar y ampliar las herramientas de diagnóstico para determinar las necesidades nutricionales y el diseño de programas efectivosde acuerdo con las condiciones particulares de cada región y los genotipos sembrados. Este recorrido conceptual deja en evidencia el vacío teórico y experimental existente para la identificación de los factores que determinan el estado nutricional de las plantaciones y su efecto en la implementación de los programas de fertilización usados en la actualidad.Información que en conjunto brinda elementos para abordar de manera adecuada esta práctica agronómica y la incidencia económica en los cultivadores y la cadena productiva del cacao.

Palabras clave: diagnostico nutricional, distribución mineral, elementos esenciales, eficiencianutricional, fertilización química/orgánica

INTRODUCTION

Theobroma cacao L. (Malvaceae) is a species native to the tropical rainforests of South America (Zarrillo et al., 2018). This fruit crop reaches its productive age in 3 to 5 years of development, with a life cycle of between 25 to 40 years (Van et al., 2015). Cacao beans are the primary raw material for producing food products such as chocolates and confectionery as well as, an emerging and growing market for cosmetic and pharmaceutical products (Quek et al., 2020). In 2019 the global market value of the chocolate industry exceeded US$13.58 billion and continued to increase as the population grows, with expectations of reaching US$15.08 billion by 2024 (Suh & Molua, 2022). Currently, *T. cacao* is an important cash crop in many tropical countries (Fountain & Huetz-Adams, 2018). Its production is concentrated in Africa (63.2%), followed by Asia (17.4%) and Latin America (14.1%), where Ecuador and Brazil are the major producing countries (Wickramasuriya & Dunwell, 2018).

In Colombia, cacao is grown in 29 of the 32 departments of the country; for the year 2020, 188 thousand hectares of planted areas were registered and distributed in the departments of Santander (41%), Antioquia (9%), Arauca, Huila (8%), Tolima (7%) and Nariño (5%) (MADR, 2021). The national average production in the last ten years was 46 thousand tons. However, for the year 2020, it was close to 63 thousand, distributed mainly in the departments of Santander (26 thousand tons), Antioquia (5 thousand tons), and Arauca (5 thousand tons), which on average register annual productivity of 500 $kg.ha^{-1}.year^{-1}$ (MADR, 2021). Our country has the ideal agroecological and climatic conditions for cultivating cacao since it has different thermal floors and is located in the equator belt, a geographical area with the temperature and humidity conducive to the growth of this plant species (Escobar et al., 2021). This frame has prompted the National Government and growers to make significant bets on strengthening a sector with great economic potential and growing demand worldwide (Escobar et al., 2021).

Despite having achieved significant progress in hectares planted with an increase in productivity during the last five years, the country only represents 1% of world production, placing Colombia as a country with low competitiveness in the cacao agricultural chain (Abbott et al., 2018). Among the main reasons for this productivity are factors such as the advanced age of the crops, the planting of hybridand common cacao with little tolerance to pests and diseases, the low density of trees per hectare, the small number of cultivated areas, the lack of tech in crop and inadequate management of the nutritional plans of the trees (Sánchez et al., 2019).

As one of the main lines of work to face the technical and productive difficulties of this crop, the intervention in the elaboration of nutritional plans has been proposed considering the genotypes sown and the edaphoclimatic conditions of the different country regions (National Federation of Cacaoteros [FEDECACAO], personal communication, May 2021). The nutritional status of plants depends on factors such as the physical-chemical and biological characteristics of the soil, water availability, climate, crop management, and the features of each genotype (Van et al., 2015). In Colombia, some of these characteristics are limiting factors, mainly the low availability of water and acidic and nutrient-poor soils (León-Moreno et al., 2019).

Fertilizers have traditionally been recommended to overcome soil nutritional deficiency (Snoeck et al., 2016; FEDECACAO, 2018). Several studies show that formulations that supplemented the primary nutrients in soils, such as nitrogen (N), phosphorus (P), and potassium (K), have significantly increased cacao productivity (Puentes-Páramo et al., 2014a; Álvarez-Carrillo et al., 2016). However, even an additional contribution is made to the soil; plants are not always efficient in using mineral elements, which directly impacts soil degradation and water pollution. Therefore, in addition to the over cost it generates in production, it significantly affects the economic viability of productive projects. In Colombia, cacao production has been classified as a peasant economy: small and medium producers. Around 52,000 families are part of this agricultural chain. They mainly belong to a low social stratum, with an explicit limitation for the implementation of optimal fertilization programs and sustainable framing practices for crop management. This context admits the need to implement different biotechnological strategies to improve crops' nutritional status. They could including the selection of elite materials, the improvement of plant material, and efficient clonal propagation systems, with solutions framed in our socioeconomic context that tend towards a more profitable, productive, environmentally and economically sustainable agricultural system.

Considering the importance of nutrition in cacao crops, the objective of this publication was to review the different findings published to date in the scientific literature regarding the factors that determine the nutritional status of cacao crops, emphasizing the publications reported on the countryand its neighboring countries. Besides analyzing the nutritional contributions of fertilization programs and theimportance of adequate diagnosis. Information that together seeks to provide elementsfor a more critical and in-depth understanding of the proper management of nutrition and its possibleeconomic impact on cacao farmers. It also encourages the implementation and development of research programs that provide the elements for the sustainable increase of crop productivity and provides bases to intensify research efforts in this area of knowledge.

DISTRIBUTION AND FUNCTION OF MINERAL ELEMENTS IN THE CACAO PLANT

In forming the plant structure in cacao trees, the absorbed nutrients are destined to develop and consolidate their different vegetative parts, such as roots, trunk, branches, and leaves. The absorptionof nutrients of greater consumption, such as N, Ca, K, P, and Mg, increases in the first five years of planting until they reach full vegetative development; from this stage, the nutrients translocated for the flowering and fruiting of the plant (Salvador et al., 2012; Romero, 2018).

In cacao plants, the nutrient content differs significantly in the tree parts, finding that it is higher in the leaves and pods, while the stem and branches show lower values (Leiva-Rojas & Ramírez-Pisco,2017; Romero, 2018). Different works agree on how nutrients are distributed in cacao leaves. Amongthese investigations, Leiva-Rojas and Ramírez-Pisco (2017) analyzed some cultivars in Colombia,the following distribution of nutrients in the leaves, N: 1.4% - 2.2%; K: 1.2% - 2.2%; Ca: 0.8% - 2%, Mg: 0.33% - 0.9%, P: 0.13% - 0.20% and S: 0.07% - 0.27%. Based on the above analysis, the authors propose the following order of content, N ≥ K ≥ Ca > Mg > P> S, making the proviso that this can change depending on the age of the crop. In this sense, Puentes-Paramo et al. (2016a) reported that this order can be variable depending on the genotype; for example, for the genotypes ICS-95 and ICS-39, this order of content Ca>N>K>Mg was found; while in TSH-565 the following order N,>Ca>K>Mg was presented, which is reversed for K and Ca in the genotype CCN-51. All the genotypes studied showed a very similar affinity for the rest of the nutrients (P, S, Mn, Fe, Zn, Na, B,and Cu). Previous work suggests that the elements' distribution values may vary depending on the planting material. However, those required in a more significant proportion for the vegetative growth of trees are N, K, and Ca.

The pods, including the bean and the husk, represent the most significant nutrient extraction for cacao plants. Different studies have calculated the number of nutrients removed per 1000 kg of dry grain (Table 1). Showing on average that the seeds remove in greater quantity N, in a range between 20 $kg.kg^{-1}$ and 24 $kg.kg^{-1}$, and it is suggested in general terms an order of extraction as follows, N>K>P>Mg>Ca>Zn=Mg>Fe>Cu>B. On the contrary, the analyses that also consider the shell reportthat K is the nutrient found in the highest concentration, ranging between 45 $kg.kg^{-1}$ and 50 $kg.kg^{-1}$ (Table 1). This means that high amounts of K are required to format the fruit. Therefore, it is the element that must be added to the soils in greater proportion during the production stage.

Regarding the function of mineral elements in plants, it is known that the 16 elements considered essential play different biochemical and biological roles for plant species (Maathuis & Diatloff, 2013). Furthermore, some nutrients have specific functions in cacao plants. In most crops, **nitrogen** is one of the nutrients required in the in the most significant quantity for cacao. It is essential for the vegetative growth of trees, drives the development of branches and leaves, and represents the highest percentage in the almond (Puentes-Páramo et al., 2014a; Furcal-Beriguete, 2017). Its deficiency reduces the leaf formation rate and accelerates defoliation, so an adequate supply of this element helps combat the progressive death field (Santana & Cabala-Rosand., 1982). It should be noted that mature trees can only respond to N when pruned (van Vliet et al., 2015).

Phosphorus is necessary for developing roots, wood, young shoots, and flowering. The deficiency of this element generates small plants, narrow leaflets, and early and severe defoliation. The application of P in cacao increases the flowering (Asomaning et al., 1971) and dry matter production (Ofori et al., 2017). On the other hand, it has been found that there is an interactionbetween N and P, where a greater radius of N/P increases cacao yields, and the lack of response to the supply of N may be due to the scarcity of

P and vice versa, a response that is mainly due to the affectation in the development of the roots to the deficiency of this element (Wessel, 1971; Puentes-Páramo et al., 2016a).

For its part, **potassium** is of great importance in the physiological processes of cacao plants, particularly for the development and pods maturation, which accumulate large amounts of this element, so the quality of cacao depends mainly on the supply of field (Furcal-Beriguete, 2017). Furthermore, K comprises about 70% of the minerals in the xylem sap of cacao and is found in branches, stems, and roots, turning these into reserve organs, which the plant can access to take K when needed. Additionally, its deficiency generates greater susceptibility to water deficit (Wang et al., 2013). In experiments on cacao seedlings, it was found that sodium (Na) could partially replace K, with beneficial effects on photosynthesis and water use efficiency. This further suggests that Na might be more efficient than K in the closing and opening stomata process, leading to lower susceptibility to drought conditions (Gattward et al., 2012).

Calcium is essential for the development and vigor of stems, young roots, shoots, and terminal flowers. It increases the shelf life of harvested fruits and organs (Jadin & Snoeck, 1985, cited by Snoeck et al., 2016). Malavolta et al. (1997) describe that high levels of Ca in the soil increase the foliar concentrations of Ca, Fe, Zn, and Mg, but decrease other nutrients such as N, Mn, and Na. **Magnesium**, this element is indispensable for photosynthesis. Particularly in cacao, a prolonged period of magnesium deficiency causes older leaves to fall off while young leaves are notaffected, causing trees to defoliate quickly (Chepote et al., 2013).

Finally, among macronutrients, commercial formulations for cacao contain **sulfur**. For cacao, there needs to be precise information on the requirements and application of this element. López & Lucas (2018)included in their research the application of concentrations of S and other mineral elements, finding improvements in the response of trees to primary diseases and crop productivity. It is essential to point out that this element in our region needs to be understood since the requirements have not been established yet.

More information needs to be published to understand the influence and importance of micronutrients in cacao nutrition, and their deficiencies, which are generally not identified in the crops (Cruz et al., 2015). Micronutrient deficiencies in the soil are not only presented by the scarcity of the different elements, but also by factors such as pH or high concentrations of other minerals that affect their bioavailability (Bonilla, 2008). For cacao, some work has been carried out to recognize the importance of these elements. For example, Boron is crucial for forming cacao fruits, and the application of borax (4.4g/tree) generated an increase in yields by 180% in a cacao plantation on Ivory Coast (Snoeck et al., 2016). Furthermore, cacao trees have generally been reported to have minimum threshold of 0.2 mg/kg of soil-soluble B. Further suggesting that soil analyses are more reliable than foliar analyses in determining a deficiency of this nutrient B-deficient cacao soils showing reductions in yield of up to 40%, with the presence of deformed fruits, short internodes, brittle leaves, and reduced seed size; in addition to greater susceptibility to black pod disease (Lachenaud, 1995).

On the other hand, Zinc is a crucial element for the activity of several enzymes. It has been shown to have a differential impact on the growth of cacao seedlings and the accumulation of other elements at the foliar level, such as P, K, Ca, Mg, Mn, Fe, Zn, and Cu. However, high concentrations of this element can cause a reduction in plant growth (Cruz et al., 2015).

Based on the work made in cacao so far, it is possible to approach the understanding of the participation of each of the nutrients, considering their participation in the building of the different plant organs. They also provide valuable elements to answer the question of how much the plant needs to build its biomass, foliage, roots, and fruits. However, it is a complex parameter that requires the integration of different factors such as genotype, edaphoclimatic characteristics, agricultural practices, etc., which allow the consolidation of a more accurate profile.

Table 1
Nutrient concentration in seeds and pods for different cacao genotypes grown in different regions of Colombia and America.

Nutrients concentration in seeds*											
Genotype	N	P	K	Ca	Mg	Mn	Fe	Cu	Zn	B	Country/ Reference
			Kg					g			
8-year-old cacao trees	24	5.1	11	1.2	3.6	23.3	26.2	21.1	43.5	-	Colombia /(Leiva-Rojas & Ramírez-Pisco. 2017)
CCN51	21.88	4.72	11.11	-	-	-	-	-	-	-	Colombia/ (Puentes-Páramo et al., 2014a)
TSH-565	20.60	5.01	10.76	-	-	-	-	-	-	-	
ICS-39	23.10	4.95	13.58	-	-	-	-		-	-	
ICS-95	23.57	6.00	15.95	-	-	-	-	-	-	-	
ICS-95	23.50	6.12	10.8	1.92	3.65	50.8	55.3	36.2	42.5	28.7	Costa Rica /(Furcal-Beriguete. 2017)
IMC-67	23.4	6.37	10.83	0.89	3.89	41.2	67.0	42.5	57.2	29.1	
PMCT-58	23.69	5.47	10.10	1.02	3.60	40.2	54.8	42.5	52.7	20	
CC-137	23.75	5.60	11.62	1.32	3.45	52.3	62.3	45.7	48.7	20	
CATIE-R1	22.73	6.13	10.57	1.0	3.73	46.7	47.0	38.8	48.7	26.3	
CATIE-R4	22.50	6.17	11.07	1.62	3.42	36.8	64.0	39.3	54.7	20	
CATIE-R6	25.22	6.05	10.99	1.12	3.35	41.2	62.2	37.2	53.3	23.5	
PH-16[b]	26.37	2.66	7.82	2.70	2.08	28.0	30.0	21.0	30.0	-	Brazil /(Araujo et al., 2017)
Nutrients concentration in Cob shell + seed[c]											
IMC-67	35.9	8.2	47.6	4.2	7.7	211.5	169	60.3	118	64.3	Costa Rica /(Furcal-Beriguete. 2017)
CC-137	34.9	7.3	50.6	5.3	6.8	261.3	135	65.8	118	76.5	
CATIE-R6	37.8	7.9	48.2	5.1	7.0	244.7	108.	54.3	114	58.7	

For seeds the concentration of each element is based on 1000 kg of dry grain. The values presented in the table are those obtained in the best fertilization program in each of the studies. [b]The values presented in the micronutrients for this clone are expressed in mg/kg. [c]Nutrient extraction for one tone of dried seeds including cob remains.

NUTRITIONAL EFFICIENCY

Nowadays, the bet is to look for environmentally friendly production technologies to improve the competitiveness of the cacao chain. One of the alternatives is to use the genetic resources available to the country to identify, characterize and select materials tolerant to nutritional stress. It has been identified that during the domestication of plant species and varieties, they have differences concerning nutritional requirements. From an agronomic approach, it has been translated to the efficiency of using nutrients, an essential characteristic for selecting and improving elitevarieties (Shin, 2014; Wang & Wu, 2015). Nutritional efficiency is defined as the maximum yield that can achieve by growing in nutrient-poor soils (Reich et al., 2014). These nutrient-efficient plants can absorb more nutrients from the soil (uptake efficiency) and produce more dry biomass per unit of the absorbed nutrient (utilization efficiency) (Reich et al., 2014).

Few nutritional studies for cacao plants have been carried out to date. These studiesshow that certain genotypes can be more efficient in taking N, P, and K from the soil and respond differentially to fertilization programs, achieving in some genotypes optimal growth and high yields inproduction (Ribeiro et al., 2008; Puentes-Páramo et al., 2014b; Li et al., 2015; Cuenca-Cuenca et al.,2019; Rosas-Patiño et al., 2019). In the same line as these studies, Ofori et al. (2017) demonstratedthat several cacao genotypes have physiological differences that allow them to develop well in marginal conditions, with low irrigation and nutrient scarcity, managing to identify potential varieties for future genetic improvement programs; despite not determining nutritional efficiency.

These studies set remarkable aspects to study the depth of the nutrition component. Nutritional efficiency has yet to be identified and characterized for selected Colombia's cacao genotypes ascultivars. There needs to be more information on the molecular, cellular, and physiological processes associated with nutrient uptake, translocation, and use. Such information is necessary for selecting clones and developing future genetic improvement programs. The selection of new clones and the cultivation of nutrient-efficient genotypes represent a sustainable approach to the nutritional management of agricultural systems, which aims to reduce soil degradation, minimizing the application of chemicals,as a commitment to a cleaner and more environmentally friendly production. Look for increased crop yields, but with economically viable technologies that benefit both small and large producers. It could be one of the strategies to make cacao crops feasible as a business model that promotes the economy of the agricultural sector in our country.

CHARACTERISTICS OF CACAO SOILS

The nutritional status of plants depends mainly on the physical, chemical, and biological propertiesof soils (van Vliet et al., 2015). For cacao trees to grow appropriately and generate maximum productivity, plants must form a broad root system, with thick root and lateral roots found in the upper20cm of the soil, which is the primary pathway for nutrient and water uptake (Hartemink, 2005).To establish a productive orchard in Colombia, it has been suggested to select soils with physical- chemical parameters close to those determined as appropriate for optimal crop development (Table 2, Table 3).It should be noted that these values may vary slightly depending on the edaphoclimatic conditions of each region, as well as the genotype sowed (Rosas-Patiño et al., 2019).

In Colombia, cacao crops are present in several departments, with notable differences in soil types, some of wich have characteristics close to those appropriate for the cultivation of the species. While in others, it is necessary to apply amendments, fertilizers, and lime to improve the structure of the soil, replace some nutritional deficiencies, and correct pH values.

The optimal soil properties reported to date point to adequate management based on clear criteria for its agricultural destination and financial sustainability of long-term productive projects for cacao crops. However, information in this area is not enough, given the wide range of agroecological environments in which crops grow in Colombia (García et al., 2004). These shortcomings in the information raise the importance of increasing and deepening studies that expand the characterizations of Colombian soils.To date, the impact of different management practices in response to cacao crop yields has been evaluated, especially using elite regional materials that have demonstrated important agronomic characteristics but have not yet been addressed in this type of research (FEDECACAO, 2018).

Table 2

Optimal physicochemical properties of the soil for proper development of cacao crops in Colombia.

Land Properties	Appropriate values for Colombia*	Importance
Texture	**Clay – Loam.** Sand:50%, Clay:30%, Limo:20%:	-Good organic matter contents. -Adequate aeration, infiltration, drainage, and moisture. -Availability of nutrients.
Effective depth	**1.5meters**	-Allows the correct development of the pivoting cacao root.
Bulk density	**1.2g/cm^3**	-Adequate permeability and drainage.
Total porosity	**10% a 66%**	-Good aeration. -Infiltration capacity of H_2O. -Development optimum of the roots. -Access of the roots to nutrients.
pH	**6.0 – 6.5**	-Neutralization of Aluminum. -Availability of nutrients. -Decomposition of organic matter.
Percentage of Organic Matter	**>5%**	-High presence of leaf litter in the surface layer, the thickness of the humus layer, and the rest of the horizon A, more than 10cm[b]. -Guarantee the presence of essential nutrients and beneficial organisms for the crop. -Improve the physicochemical properties of the soil.

[*] Reference values for Colombia suggested by the National Federation of Cacao Growers (FEDECACAO, 2013; FEDECACO, 2018), some values were specified with other bibliographic sources (Snoeck et al., 2016).

NUTRITIONAL CONTRIBUTIONS TO CROPS

AGROFORESTRY SYSTEMS IN CACAO

Cacao is naturally adapted for semi-shade in the understory. The photosynthetic process in the leaves is saturated with light is set between 500 and 600 μmol.m^{-2}s^{-1} of photosynthetically active radiation (PAR) (Baligar et al., 2008; Ávila-Lovera et al., 2016). In Colombia, solar irradiance can vary significantly between cacao-producing regions, from 287.5 μmol.m^{-2}s^{-1} to 1341 μmol.m^{-2}s^{-1} (IDEAM, 2019). Therefore, establishing agroforestry systems for this crop is essential for controlling light and providing the right conditions for optimal plant development.

Agroforestry systems are crucial to meeting the shade needs of the species and are the main factor affecting yield. Under the shade, plants can have slightly lower yields but with constant values over time, in addition to a longer life span of the plantations. Likewise, this cultivation scheme represents additional benefits to the ecosystem, such as improved soil fertility, erosion management, biodiversity conservation, and carbon storage (Mortimer et al., 2018). Services that together positively impact crop development and growth directly impact crop yields.

The plant species accompanying cacao cultivation in agroforestry systems play a crucial role in the nutritional dynamics of the system. Borden et al. (2020) demonstrate that the expression of the different functional traits of cacao roots and the nutrient acquisition patterns are closely related to the agroforestry species that accompany the crop. Similarly, other authors indicate that thenutritional status of cacao trees is significantly modified by interactions with shade trees (Isaac et al.,2007). One element that demands greater concentration in plant species, including cacao, is N, so it is recommended to use as shade species of legumes fixing gaseous nitrogen (N_2). This practice can significantly contribute to this element and generate a good proportion of deposition of leaves, branches, and flowers, increasing the accumulation of organic matter on the surface and favoring microfauna. For example, *Inga edulis* Mart (Fabaceae) was found to have an N_2 fixation rate of 41 $kg.ha^{-1}.year^{-1}$.This plant directly transfers nitrogen to the cacao roots through a common mycelial network of mycorrhizal fungi and recycling N-rich root exudates that generate an average contribution of 50 $kg.ha^{-1}.year^{-1}$ of the N present in the cacao roots (Nygren & Leblanc, 2015).

Another essential element is P, Aleixo et al. (2017) found that there is a significant accumulation of total inorganic and organic phosphorus in cacao crops associated with *Erythrina* spp (Fabaceae), compared to cabruca-plus-cacao-type forest cover; with an average amount of P in the labile fraction of 51 $kg.ha^{-1}$ and 33.5 $kg.ha^{-1}$, respectively. A similar result was obtained with crops associated with *Hevea brasiliensis* Müller Argovi (Euphorbiaceae), which accumulated 41 $kg.ha^{-1}$ of P in the labile fraction amounts to replenish the nutrients exported by cacao seeds (Table 1). This evidence suggests that the different plant species that make up agroforestry systems have the potential to supply the P required by cacao plants through the mineralization process in case of suppression of phosphate mineral fertilization (Aleixo et al., 2019). These studies together point to the importance of this agricultural practice being developed under a solid ecological foundation, aiming to maintain an adequate nutritional balance for the entire system.

Table 3

Reference levels of different physicochemical parameters for cacao soils in Colombia and other regions of the world.

Parameter/ Reference	(León-Moreno et al., 2019) [a]	(García et al., 2004) [b]	(Snoeck et al., 2016) [d]	(van Vliet and Giller 2017) [f]	(Araujo et al., 2018) [g]
pH	5.0	5.5	5.1	5.5	5,5
MOS (%)	3.0	>4.0	2.93	2.57	45[g]
N (total %)	----	----	0.2	0.15	----
P ($\mu g.g^{-1}$)	12	13	6/12[e]	10	20
Al ($cmol_c.kg^{-1}$)	<1.5	< 40[c]	>1.5	----	0.0
Ca ($cmol_c.kg^{-1}$)	4.0	>4.0	4.0	8.0	3.0
Mg ($cmol_c.kg^{-1}$)	1.0	1.0	0.9	2.0	1.0
K ($cmol_c.kg^{-1}$)	0.2	>0.3	0.2	0.2	0.25
CEIC ($cmol_c.kg^{-1}$)	6.0	----	12.0	----	8.0
Country	Colombia	Colombia	-----	----	Brazil

[a]Minimum values of chemical conditions in Colombian soils for the development of cacao production projects. [b]According to the classification of authors, these values correspond to moderately suitable characteristics. [c]Percentage of saturation of Al. [d, f]Recommended values based on different studies worldwide, which may vary according to each locality and genotype. [e] Values obtained by Mehilich/Olsen extraction methods. [g] Organic matter in $g.Kg^{-1}$.

NUTRITIONAL CONTRIBUTIONS FROM ORGANIC AND INORGANIC SOURCES TO CACAO SOILS

The high extraction of nutrients during the harvest of cacao pods generates a significant decrease in soil fertility, which cannot be compensated by the contributions provided by agroforestry speciesduring the first six years of cultivation (Aikpokpodion, 2010; Bai et al., 2017). If nutrients are not addedto the soil for the next harvest, it can cause a deterioration in the quality and productivity of cacao crops (Appiah et al., 2000). Besides, a premature aging of crops and susceptibility to phytosanitary problems (Ludeña-Davila, 2013; Tuesta-Pinedo et al., 2017). To maintain the required nutrients on balance in fertilization programs, complimentary use of organic and inorganic sources is necessary.

CHEMICAL FERTILIZATION

In Colombia, researches on soil and foliar fertilization in cacao is scarce and is in full development and increase due to the recent recognition of the importance of this crop for the country. Table 4 shows fertilization programs implemented in our country and other LatinAmerican countries. Here, it is observed differences in the amounts and sources of nutrients, as well as the yields obtained according to the genotype. Such results obey the various factors that impact this agronomic practice.

The first action usually implemented in a fertilization program is the management of acidity, which controls the availability of nutrients. It is also essential, especially in the soils of the tropics, where acidic soils predominate (Casierra, 2007). This management is carried out through the application oflime to increase pH values, mitigate the toxicity of aluminum, and ensure the availability of elementssuch as Ca, Fe, Mg, and P. Among other benefits that allow for the gradually restoring the soil's fertility in its chemical composition (Castro & Guerrero, 2018). An example of the effect of liming is the study done by Rosas-Patiño et al. (2017, 2019) in the Colombian Amazon's oxisol, ultisol, and entisol soils. The additions of amendments significantly improved soil characteristics, including nutrient availability and increasing cacao crop yields.

Once it is possible to balance the acids of the soil, the next step is to complement the missing nutrients in it. For cacao, the fertilization programs implemented have generally been designed to compensate for the demands of N, P, and K (Table 4). Reported studies have mostly found that the application of these elements increases production (Uribe et al., 1998; Rosas-Patiño et al., 2019), but in others, there was no significant increase in productivity (Sánchez et al., 2005).

Differential responses to implemented fertilization programs may be due to factors such as difficulties in adopting other agronomic practices, added to an imbalance in the nutrients added. Somework is forceful in demonstrating that if fertilization is exceeded, lower yields are obtained due to theantagonism between the elements, which reduces the absorption of other nutrients. For example, if N is added as a source of ammonium, the absorption of other cations such as Ca^{2+}, Mg^{2+} or K^{+}, can be reduced (Puentes-Páramo et al., 2014b; Cuenca-Cuenca et al., 2019).

Another factor that conditions the response of nutritional programs is the genetic potential and physiological and morphological characteristics of each genotype, which in turn is influenced by the edaphoclimatic conditions where the crop grows. A clear example is the results obtained in two investigations where the same fertilization program was implemented, and identical genotypes were evaluated. However, a marked difference in yields was obtained, where the most significant differentiating factor was the edaphoclimatic conditions where these crops grew (Puentes-Páramo etal., 2014b; Rosas-Patiño et al., 2019). In many crops, despite an adequate balance of nutrients, the response is genotype-dependent, of which in particular, its yields grow exponentially in different fertilization programs, which in addition to other characteristics of the genotype, adds the ability to self-fertilize, ensuring floral fertility and therefore fruit formation (Ruales-Mora et al., 2011).

In fertilization programs, physicochemical characteristics of each of fertilizers used is essential. For most plant species, including cacao, the nutrients most plants require are N, P, and K, which are the main elements found in fertilizers. Therefore, it is crucial to understand the most efficient way they are available to the plant. Generally, to supply the N, urea is applied, a very economical source of this element (Table 4). However, in Colombia acidic soils are predominant, whereby there might be better options than urea, given its high volatility and increase in soil acidification. For this reason, it is essential to consider other sources, such as ammonium sulfate ($(NH_4)_2SO_4$) or nitrates (e.g., calcium nitrate, $Ca(NO_3)_2$), which are directly available to plants and favor the uptake of other nutrients, with a lower impact on soil pH (Snoeck et al., 2016). However, its importation causes higher costs and is unprofitable.

Table 4

Fertilization programs implemented in cocoa crops in different studies describe the quantities and sources of the amendments.

Type of Crop	MO %	Initial level K cmol.kg-1	P mg.Kg-1	Fertilizer applied Kg.ha-1 N	P_2O_5	K_2O	Ca		Yields by genotype[a] Kg/ha	Country /Reference
Agroforestry System	1.92	0.11	3.89	73 Urea	35.2 KH_2PO_4	219.7 KCl	7000 lime		CCN-51: 4100 ICS-1: 3855 ICS-39: 2033 TSH-565: 2944	Colombia/ (Rosas-Patiño et al.. 2019)
Crops in full sun exposure	7.4	0.26	8.60	73	35.2	219.7	-		CCN-51: 1967 ICS-1: 1337 ICS-39: 1340 TSH-565: 1634	Colombia /(Puentes-Páramo et al.. 2014a)
Crops in full sun exposure	3.0	-	-	Urea 80 Urea	$(NH_4)_2HPO_4$ 150 $Ca(H_2PO_4)$ $2.H_2O$	KNO_3 160 KCl	0.2 kg/P Dolomite	2.0 kg.P Gallinaza	Hybrid cocoa:721	Colombia/ (Mejia & Palencia.. 2000)
Crops in full sun exposure	9.3	0.11	9	150	90	200	0.2 kg/P Dolomite	2.0 kg/P Gallinaza	Commercial hybrid blend:1160	Colombia (Uribe et al.. 1998)
Crops in full sun exposure	1.7	0.81	24	74 Urea	37 $(NH_4)_2HPO_4$	148 KNO_3			EET-576:1430.3 EET-575:1363 EET-103: 902.2- CCN-51:2388.8	Ecuador (Cuenca-Cuenca et al.. 2019)
Crops in full sun exposure	3.8	0.61	28	450	50	200			Average for three clones (EET–103. EET-575 and EET–476): 2334.09	Ecuador/(Cedeño et al.. 2017)[b]
Agroforestry System				Urea 120	- 100 Island Guano	- 160 K_2SO_4			CCN51: 1408.51	Peru/(Ludeña-Davila. 2013)[c]

[a] *Although the references cited in the table evaluated other sources and concentrations of fertilizers. the conditions under which the highest yields were achieved are reported here.* [b] *This fertilization program also added: 100 Kg gypsum 5 kg/h Borzax and 5 kg/Zinc Sulfate and 0.5 L/ha of phytoregulators. which together were the best nutritional combination.* [c] *This fertilization program also added 25g of MgO. 150 g S. 5g Br. 0.5 g Zn. 0.5 g Cu and 1.0 g Mn.*

Regarding the sources of P used for cacao, among them are the phosphoric rock ($Ca_3(PO_4)_2CaF_2$ and the triple superphosphate $Ca(H_2PO_4)_2{\cdot}H_2O$ (Table 4), which are good sources of P and also increase the pH of the soil. However, some studies indicate that care should be taken in the form and amount in which this element is added, taking into account the pH value and the proportion of K-Ca-Mg found in a particular soil. These phosphoric fertilizers rich in CaO can create an imbalance in the proportion of several cations and even precipitate the same P, forming calcium phosphates.

On the other hand, K is the nutrient added in greater concentration due to its high demand for the formation of the cacao fruit. Therefore, due to its low costs, one of the most used sources in crops is potassium chloride (KCl). However, Cl can be phytotoxic and, contributes to soil acidification due to its easy leaching (Snoeck et al., 2016). Other common sources of this element are K_2SO_4 and KNO_3; both can be excellent sources of K and other nutrients such as S and N. In addition, these sources do not interfere with the absorption of other ions and have high solubility. Nevertheless, these K sources are more expensive and can increase the cost of production.

Finally, although macronutrients N, P, and K are the elements that are added in a more significant proportion in fertilization programs, the other macroand micronutrients are of equal importance at the physiological level. Unfortunately studies evaluating the impact of micronutrients on cacao crop yields are scarce. For example, supplementing elements such as B and Zn significantly increasing yields in different cacao genotypes (Ludeña-Davila, 2013; Cedeño et al., 2017). It also demonstrates that B deficiency limits the complete filling of the fruits, affecting the cob index, a key parameter with which crop productivity is evaluated (Lachenaud, 1995).

ORGANIC FERTILIZATION

Another important source of nutrients to meet the nutritional demands of cacao are organic fertilizers, which are a significant source of nutrients for this crop. Different soil properties improve themselves, such as the rate of water infiltration, aeration, and moisture retention capacity, among other characteristics, which facilitate the growth of the root system and, transport nutrientsto the plant (Diacono & Montemurro, 2010). Although organic fertilizers are less soluble and have a slow decomposition, it is not inconvenient for perennial species such as cacao, which can take advantage of the nutrients that gradually solubilize in the soil solution.

Organic matter addition is calculated from the amounts of nutrients provided by organic compounds. High volumes are generally required to exercise their function as soil improvers and provide nutrients. In several cacao-producing regions, such as Côte d'Ivoire, Indonesia, and Peru, the application of high amounts of cob shell compost has been shown to represent an essential contribution to the recycling of nutrients in the system, with a direct impact onincreasing crop yield. For example, a study conducted in oxysol soils in Brazil showed that using 8 tons/ha/year of cacao husk compost promoted a 133% increase in dry grain production compared to treatment without fertilization (Chepote, 2003). Likewise, the application of 4 kg.plant^{-1}.year^{-1} of a mixture of cacao cob shell, livestock manure compost, and 50% mineral fertilizer (13%N, 35%P_2O_5, and 10% K_2O) promoted an 188% increase in production.

For Colombia, there are few studies where organic fertilizers are evaluated replace chemical fertilizers. For example, Álvarez et al. (2016) demonstrated an increase in the height and diameter of the stem for cacao plants at the growth stage. It was obtained with an organic fertilizer consisting of banana stem, cane bagasse, and bovine manure, among other elements, which were an good source of nutrients for cacao plants.

Compiling the works in both types of fertilization, chemical and organic, allow us to demonstrate that fertilization must be evaluated integrally which is essential considering the crop yields and the availability of nutrients. Furthermore, the impact of these nutrient sources might generate on the soil, biota, the environmental impact and the economic expenses t each represents. Therefore, this consideration aims to reduce dependence on external inputs and maintain a balanced ecosystem with high crop yields.

FERTILIZATION PROGRAMS IN THE NURSERY STAGE

In most cacao-producing countries, crops are made up of trees that were grafted in the initial stageof their development, requiring two types of plant materials, rootstock, and scion. The first is obtained from seed and the second from tree branches (Guiltinan et al., 2015). Proper growth of plants during the nursery stage might ensure optimal physiological and sanitary characteristics and good performance in the field. One of the first works carried out in nutrition was done by Thong & Ng (1980), whom designed a fertilization program for this stage of the crop. In a recent study conducted by Fernández et al. (2016), with seedlings of the IMC-67 rootstock, the same nutritional plan of Thong & Ng (1980) was evaluated. The authors found overfertilization of the seedlings, demonstrating that supplementing only with 50% of N and K concentration suggested in the previous work could achieve a more significant amount of biomass. Other studies indicate adding high amounts of some of these nutrients. However, in light of the additional research carried out on the subject (Table 5), it is considered that some concentrations of the mineral elements could be toxic to plants at this stage of development.

Based on the above, there is a lack of consensus regarding the nutritional plans for cacao plants in this stage of development. Such a fact may be due to several factors, including the specific nutritional demands of each genotype, the type of substrate used, and the differences in environmental conditions in the greenhouse. Likewise, a deep knowledge of the nutritional dynamics of macro and micronutrients is required. To date most studies focusing on the evaluation of N, P, and K. Which has led to leaving aside crucial nutrients such as Zn, Mg, and B at this stage of development, as has been shown in different studies (Sodré et al., 2010; Ludeña-Davila, 2013; Cruz et al., 2015). These shortcomings of knowledge in this area make a call to encourage the development of research that allows determining, among other factors, the appropriate nutritional formulation for this stage of development, the type of substrate, container, and the requirements of light, temperature and wet.

Table 5

Nutritional requirements of cocoa in the nursery stage determined in different studies.

Genotype	Experiment conditions	Nutritional requirements g/plant	Country/ Reference
IMC-67	-Substrate: 3kg soil and sand: 1:1. Soil inceptisol. -Nursery conditions: 12hours or natural light at 60%; relative humidity: 83%; average temperature; 25 ºC. -Freshly germinated seedlings.	-N: 0.6-Urea: 1.3 -P: 0.3-SPT: 1.52 -K: 0.7-KCl: 1.205	Colombia/ (Fernández et al., 2016)[a]
Various genotypes	-Substrate: 3kg soil. -Seedlings 75 days old.	N: 3; P: 9; K: 6	Colombia/(Palencia et al., 2009)
PBC-123	-Substrate: mixture of soil and sand with 40% final clay. -Freshly germinated seedlings.	N: 1.2; P: 0.5; K: 1.4; Mg: 0.4; Ca: 1.3	Indonesia/(Oberthür et al., 2018)
Various genotypes	-Plants between 5 and 12 months of age.	Urea: 2.6; Tax Return:1.52; KCl: 2.41	Malasia/(Thong & Ng, 1980)
Common rootstock	-Red-yellow Argisol soil.	N:5; P_2O_5:12; Ca:12; Mg:1,5; S:5; Zn:2; B:1.5, Cu:0.5; Mn:0.5; Mo:0.2; Fe:0.1	Brasil/(Sodré et al., 2010)[b]

[a]Nutrient concentrations in g per plant, these dates are one approximation and were calculated from the data published in each study. [b] Values presented are expressed as a percentage.

DIAGNOSIS OF NUTRITIONAL STATUS IN CROPS

Traditionally, tools such as foliar nutritional concentration and the physicochemical parameters of the soil have been used to know the nutritional status of crops. These tools contribute to understanding the nutrient dynamics in the soil, plant nutrient uptake, and their use in different physiological processes, which has served as the basis for the design of fertilization programs. Currently, there are available new approaches with outstanding contributions due to their novelty and the inclusion of various variables. Among them, we find the soil quality index, a more holistic and in-depth analysis of soil characteristics and their relationship to the ecosystem. Likewise, mapping for the identification and management of crop areas, as a tool for the identification and delimitation of areas in the same crop, which have differences in their fertility, provides instruments to do precision agriculture.

DETERMINATION OF THE FOLIAR CONCENTRATION OF NUTRIENTS

Overall, the leaves reflect the nutritional status of a plant better than other organs. However, factors such as the type of nutrient, age, and plant species may suggest sampling in another organ or part of the plant (Garate & Bonilla, 2008). For cacao, determining the concentration of minerals in leaf tissue has been widely used to indicate the plant's nutritional status (Puentes-Páramo et al., 2016b; van Vliet & Giller, 2017). For this purpose, well-described protocols for sampling and validated analytical methods for the quantifying the different elements have been reported (INIAP, 2016; Motsara & Roy, 2008).

In this process, the interpretation of the results of a foliar analysis consists of comparing the data obtained with reference values established in crops with high yields. These comparisons allow us to identify different nutritional conditions in the plant, such as deficiency, sufficiency, luxury consumption, and toxicity (Osorio, 2012). For cacao crops in Colombia, the reference ranges of the concentration of the different elements at the foliar level were recently proposed, which tend towardsa correct nutritional balance in the plant (Table 6). Comparing these values with those reported in some studies in Brazil, there is a similarity in the reference values for macronutrients but marked differences in the concentrations of micronutrients (Table 6).These works suggest the great importanceof conducting studies for each of the regions of Colombia where cacao cultivation is present and not incurring generalizations for determining nutritional requirements through this tool.

This tool has shown a relationship between the nutritional status of the foliar diagnosis and the other parts of the tree, particularly in cacao crops, but there are certain limitations. For example, cacao fruits grow along the stem taking the nutrients before they reach the leaves, making it possible for theleaf tissue not to receive the necessary nutrients. Therefore, the foliar analysis may suggest nutritionaldeficiencies. Likewise, water and nutritional competition between the cambium of the trunk, branches, fruits, and leaves may change the nutritional dynamics. These plant dynamics could lead to an erroneous interpretation of this analysis can be given (Snoeck et al., 2016).

DETERMINATION OF THE PHYSICOCHEMICAL PARAMETERS OF THE SOIL

In diagnosing soils, the physical and chemical characteristics are evaluated, and in some cases, are added some biological measures. The procedure for their sampling and the analytical methods for determining the different parameters are well described and standardized (FEDECACAO, 2018; Motsara & Roy, 2008). Soil fertility is determine by comparing the results with reference values explicitly built for each plant species grown in different fertilizer matrices and soil types. Therefore, the result of this analysis allows us to correct each nutrient concentration in the soil. Assuming that crop growth and productivity will be optimal if each nutrients within these limits.

In the case of cacao crops in Colombia, they have been described the main physicochemical characteristics and nutrient content a soil must have in suitable conditions (Table 2 and Table 3). However, the reference values used for interpreting this analysis may change according to local environmental conditions and cultivated genotypes. To validate reference values is necessary to carry out dose-response experiments with different types of soil, covering these dynamics in the soil-plant relationship (van Vliet & Giller, 2017). In the different cacao-producing regions in Colombia, this type of research has yet to be carried out, which limits the more precise definition of the nutritional needs of cacao under different environmental conditions.

Table 6

Ranges to interpret foliar analyses in cocoa. The values presented represent the concentrations in which each of the elements must be found in the leaf tissue to consider that there is no deficiency or toxicity of the element in the plant.

Nutrients/Reference	(Puentes-Páramo et al., 2016a) .	(Abreu-Junior. 1996)	(Malavolta. Vitti. & Olveira. 1997)	(Sodre et al., 2001)
Macronutrients (g.Kg^{-1})				
N	16.1-18.3	17.7-21.9	19.0-23.0	23.4-24
P	1.2-1.9	0.9-1.2	1.5-1.8	2.1-2.2
K	9.1-12.7	3.8-12.5	17.0-20.0	16.5-17.1
Like	16.9-24.5	16.7-22.2	9.0-12.0	8.3-9.0
Mg	4.4-7.1	6.4-9.0	4.0-7.0	4.3-4.5
S	2.0 -2.3	1.4-2.0	1.7-2.0	---
Micronutrients (mg.Kg^{-1})				
B	24.9-39	---	30-40	---
With	15.9-73	6.0-8.7	10-15	38.9-44
Fe	195-346	33-64	150-200	62.7-83.4
Mn	354-547	242-435	150-200	194.2-226.4
Zn	34-62	32-75	50-70	115.9-129.7
Cultivation region	Colombia	Brazil	Brazil	Brazil

These reference values have been determined in the plantations that demonstrate the highest productivity. Table constructed from the information reported by (Puentes-Páramo et al., 2016b) and other authors.

From the point of view of farmers, it is found that many need more technical advice for theinterpretation of soil analyses, which has led them to implement fertilization programs without this information, assuming an imbalance in nutrition programs and cost overruns in production. This problem has motivated some researchers to develop software that facilitates understanding and interpreting these results. To allow the formulation of balanced nutritional programs for cacao crops, consider different parameters, among them the nutrients exported in each harvest (Snoeck et al., 2007).

NEW APPROACHES TO THE CHARACTERIZATION AND FERTILITY OF CACAO CULTIVATION.SOIL QUALITY INDEX

The soil resource is an ecosystem that supports the life of multiple organisms, with a close relationship between the biota and the plant species that coexist there. Therefore, determining additional and more complex parameters in this matrix allows adequate and responsible management of this resource. For example, to determine for cacao crops the indicators that allowestablishing soil quality indices (Soil Quality Index, SQI). Araujo et al. (2018) carried out a study in the humid region of Bahia (Brazil), which has traditionally cultivated this species; there, the SQI was established based on four parameters, 1) water availability in the soil, 2) root growth, 3) mineral nutrition of plants and 4) environmental safety (presence of heavy metals). For each of these functions, many indicators were determined that allowed deeper relationships to be made in the analysis. Among the most relevant results, the highest SQI values were obtained for a cultivation site corresponding to an agroforestry cacao system, with adequate irrigation, high ion exchange capacity, and high content of available mineral elements. These are the indicators that best reflect the quality of the soil and its high potential for selecting areas where cacao can be grown.

MAPPING FOR THE IDENTIFICATION AND MANAGEMENT OF CROP AREAS

Soils generally present variations in their physicochemical properties in the same crop area, so the design of fertilization programs based only on average values can lead to errors in implementing generalized nutritional programs for the entire plantation (Silva et al., 2010). Determining the variability within a cultivation area allows the determination of management zones and, therefore, the application of precision agricultural techniques. Carvalho et al. (2016) validated the methodology for determining management zones within the same cacao plantation. They established grouping patterns between the soil properties and the yield obtained by each crop area. Among the variables that provided more information in this study was the yield of early harvest cacao and the total fractions of sand or clay in the soil with which the management zones are determined. Similarly, other authors have used soil maps to demarcate the best agroecological zones to grow cacao, linking crop requirements with soil data and thus designing accurate fertilizer recommendations (Snoeck et al., 2010; N'Guessan et al., 2017).

Similar studies have yet to be carried out in Colombia. However, the Zoning map of suitability for commercial cacao crops (Agricultural Rural Planning Unit [UPRA], 2019) was recently published. This study aimed to design a tool for consultation and identification of areas with an aptitude for establishing this crop. Furthermore, establish guiding policies for the development of the cacao sector, framed in the sustainability, competitiveness, and productivity of the cacao chain.

CONCLUSIONS

Cacao cultivation has been identified as a product of excellent projection in international agricultural markets and a good source of income for hundreds of families in Latin America, including Colombia. This review has made it possible to identify that developing an effective nutritional plan is a determining factor in improving the productivity and quality of cacao crops. It is a complex task that requires the commitment of all actors in the production chain. The studies reviewed made it possible to identify the nutritional requirements of a crop. However, the impact of fertilization programs on crop yields is strongly influenced by several factors such as genotypes' genetics, edaphoclimatic characteristics of each area, agroforestry species accompanying the crop, and agronomic practices used. All those elements suggest that there is no single fertilization program.It also should be designed with specific criteria for each plantation, using traditional tools such as foliar and soil diagnosis and other parameters with more profound and holistic analyses such as the soil quality index, and crop mapping, among other tools.

Likewise, the different works collected in this review highlight the theoretical and experimental gap between the other aspects that determine the nutritional needs of cacao crops and their effect on the programs implemented. . Whereby works in these aspects could contribute significantly to establishing a profitable and sustainable production model for cacao producers.

From the technical and scientific perspectives addressed, it has been possible to identify that, although there are specific interventions in the processes of fertilization, advice, and delivery of genotypes and elite materials to growers. These interventions have yet to manage to generate sufficient modernization of the crop. Integrating actors, such as government, private companies, and universities, is fundamental for this process. Additionally, the intervention of federations, cooperatives, and other associative schemes is critical in distributing resources and technical advice for implementing nutrition plans. Programs will be effective with the commitment of decision-makers and producers to increase their efforts in changing traditional ways of managing the crop.

Disclaimers

All authors made significant contributions to the paper, agree with its publication, and state that there are no conflicts of interest in this study.

Acknowledgments

This work was funded by the General Royalty System - Science, Technology and Innovation Fund ofthe Government of Antioquia, University of Antioquia, Catholic University of the East, National Chocolate Company with the project identified with BPIN 2016000100060.

BIBLIOGRAPHY

Abbott, P.C.; T.J. Benjamin; G.R. Burniske; M.M. Croft; M.C. Fenton; C.R. Kelly; M.M. Lundy; F.R. Camayo & M.D. Wilcox (2018). An Analysis of the Supply Chain of cacao in Colombia. United States Agency for International Development 1-69.

Abreu-Junior, C.H. (1996). Foliar nutrient concentration and rations in height yield cocoa genotypes and relations yield and intensity of witches broom disease. Cacao Research CocoaProducer´s Alliance. Conference. CEPLAC/ CEPEC. Atas.

Aikpokpodion, P.E. (2010). Nutrients Dynamics in Cocoa Soils, Leaf and Beans in Ondo State, Nigeria. Journal of Agricultural Sciences 1(1): 1-9.

Aleixo, S.; A.C. Gama-Rodrigues; M.G. Costa; M.V. Sales; E.F. Gama-Rodrigues & J.R.B. Marques (2017). P transformations in cacao agroforest soils in the Atlantic forest region of Bahia, Brazil. Agroforestry Systems 91(3): 423-437.

Aleixo, S; A.C. Gama-Rodrigues; E.F. Gama-Rodrigues & J. Schripsema (2019). Organic phosphorus of soils under cacao agroforests in the Atlantic coast of Brazil. Geoderma Regional17: e00220.

Álvarez-Carrillo, F.; J. Rojas Molina & J.C. Suárez Salazar (2016). Contribución de esquemasde fertilización orgánica y convencional al crecimiento y producción de *Theobroma cacao* L., bajo arreglo agroforestal en Rivera (Huila; Colombia*).* Corpoica Ciencia y Tecnología Agropecuaria 16(2): 307.

Appiah, M.; K. Ofori-Frimpong & A. Afrifa (2000). Evaluation of fertilizer application on some peasant cocoa farms in Ghana. Ghana Journal of Agricultural Science 33(2).

Araujo, Q.R.; V.C. Baligar; G.A.H. de A. Loureiro; J.O. de Souza Júnior. & N.B. Comerford (2017). Impact of soils and cropping systems on mineral composition of dry cacao beans. Journal of Soil Science and Plant Nutrition 17(2): 410-428.

Araujo, Q; D. Ahnert; G. Loureiro; J. Faria; C. Fernandes & V. Baligar (2018). Soil quality index for cacao cropping systems. Archives of Agronomy and Soil Science 64(13): 1892-1909.

Asomaning, E.; R. Kwakwa & W. Hutcheon (1971). Physiological studies on an Amazon shadeand fertilizer trial at the Cocoa Research Institute, Ghana. Ghana Journal of Agricultural Science 4: 47-64.

Ávila-Lovera, E.; I. Coronel; R. Jaimez; R. Urich; G. Pereyra; O. Araque; I. Chacón & W. Tezara (2016). Ecophysiological traits of adult trees of criollo cocoa cultivars (*Theobroma cacao* L.) from a germplasm bank in Venezuela. Experimental Agriculture 52(1): 137-153.

Bai, S.; S.J. Trueman; T. Nevenimo; G. Hannet; P. Bapiwai; M. Poienou & H.M. Wallace (2017). Effects of shade-tree species and spacing on soil and leaf nutrient concentrations in cocoa plantations at 8 years after establishment. Agriculture. Ecosystems and Environment 246(June): 134-143.

Baligar, V.C.; J.A. Bunce; R.C.R. Machado & M.K. Elson (2008). Photosynthetic photon flux density; carbon dioxide concentration and vapor pressure deficit effects on photosynthesis in cacao seedlings. Photosynthetica 46(2): 216-221.

Bonilla, I. (2008). Introducción a la nutrición mineral de las plantas. Los elementos minerales. In: Fundamentos de fisiología vegetal. J. Azcón-Bieto & M. Talón., Ed. Mcgraw-Hill -Interamericana de España, España. pp.103-121.

Borden, K.A.; S.C. Thomas & M.E. Isaac (2020). Variation in fine root traits reveals nutrient- specific acquisition strategies in agroforestry systems. Plant and Soil 453: 139-151.

Carvalho, P.S.M.; L.B. Franco; S. de A. Silva; G.A. Sodré; D.M. Queiroz & J.S. de S. Lima (2016). Cacao crop management zones determination based on soil properties and crop yield.Revista Brasileira de Ciencia Do Solo 40: 1-17.

Casierra, F. (2007). Estrés por aluminio en plantas: reacciones en el suelo, síntomas en vegetales y posibilidades de corrección, una revisión. Revista Colombiana de Ciencias Hortícolas 1(2): 246-257.

Castro, H. & J.C. Guerrero (2018). Evaluación de materiales de encalado mediante pruebas de incubación en un oxisol de la altillanura colombiana. Revista de Ciencias Agrícolas 35(2): 14- 26.

Cedeño, L.; A. Diogenes; V. Calderón & E. Jair (2017). Efectividad de varias combinaciones de nitrógeno, azufre, zinc, manganeso, boro y fitohormonas sobre el rendimiento y rentabilidaddel cacao nacional. Ing. Thesis. Escuela Superior Politécnica Agropecuaria de Manabí ManuelFélix López. Calceta, Ecuador. pp 11-20.

Chepote, R.E. (2003). Efeito do composto da casca do fruto do cacau no crescimento e produçãodo cacaueiro. Agrotrópica (Brasil) 15(1): 1-8.

Chepote, R.E.; G.A. Sodré; E.L. Reis; G.R. Pacheco; P.C.L. Marrocos & R.R. Valle (2013). Recomendações de corretivos e fertilizantes na cultura do cacaueiro no sul da Bahia: 2a aproximação. R. Costa Argôlo., Ed. Ministério Da Agricultura, Pecuária E Abastecimento. CEPLAC/ CEPEC. Boletim Técnico 203.

Cruz, R.; J. Souza; G. Sodré & V. Baligar (2015). Growth and nutrition of cacao seedlings influenced by zinc application in soil. Revista Brasileira de Fruticultura 37(4): 1053-1064.

Cuenca-Cuenca, E.W.; Y.J. Puentes-Páramo & J.C. Menjivar-Flores (2019). Efficient use of nutrients in fine aroma cacao in the province of Los Ríos-Ecuador. Revista Facultad Nacional de Agronomia, Medellin 72(3): 8963-8970.

Diacono, M. & F. Montemurro (2010). Long-term effects of organic amendments on soil fertility. A review. Agronomy for Sustainable Development 30(2): 401-422.

Escobar, S.; M. Santander; M. Zuluaga; I. Chacón; J. Rodríguez & F. Vaillant (2021). Fine cocoa beans production: Tracking aroma precursors through a comprehensive analysis of flavor attributes formation. Food Chemistry 365: 130627.

FEDECACAO (2013). Guía ambiental para el cultivo del cacao. pp. 1-126. Availablein: http://hdl.handle.net/20.500.12324/11622 Last accessed October of 2022.

FEDECACO (2018). Guía técnica para el cultivo del Cacao. pp. 169-192. Available in: http://hdl.handle.net/20.500.12324/11684. Last accessed October of 2022

Fernández, L.; J.C. Bohórquez & A. Rodríguez (2016). Dinámica nutricional del cacao bajo diferentes tratamientos de fertilización con N, P y K en vivero. Revista Colombiana de Ciencias Hortícolas 10(2): 367-380.

Fountain, A. & F. Huetz-Adams (2018). Cocoa Barometer. Available in: https://www.voicenetwork.eu/2018/04/2018-cocoa-barometer-released/. Last accessed July of 2022.

Furcal-Beriguete, P. (2017). Extracción de nutrientes por los frutos de cacao en dos localidadesen Costa Rica. Agronomía Mesoamericana 28(1): 113-129.

Garate, A. & I. Bonilla (2008). Nutrición mineral y producción mineral. In Fundamentos de fisiología vegetal. J. Azcón-Bieto & M. Talón., Ed. Mcgraw-Hill - Interamericana de España, España. pp. 124-143.

García, J.; M. Romero & L. Ortíz (2004). Caracterización y zonificación de áreas potenciales para el cultivo del cacao en Colombia: dirección de cadenas productivas cadena de cacao - chocolate. In FEDECACAO. Available in: http://hdl.handle.net/20.500.2324/1907. Last accessed October of 2022.

Gattward, J.N.; A.A.F. Almeida; J.O. Souza; F.P. Gomes & H.J. Kronzucker (2012). Sodium-potassium synergism in *Theobroma cacao*: Stimulation of photosynthesis; water-use efficiencyand mineral nutrition. Physiologia Plantarum 146(3): 350-362.

Guiltinan, M.; G. Lockwood; S. Maximova; A.R. Sena Gomes; G.A. Sodre; B. Laliberte; M. End & S. Weise (2015). Supplying new cocoa (*Theobroma cacao* L.) planting material to farmers: A review of cacao propagation methodologies. Bioversity International. B. Laliberté & M. End. Rome, Italy. pp. 67-87.

Hartemink, A.E. (2005). Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems:A review. In Advances in Agronomy 86: 227-253.

IDEAM (2019). Irradiación global horizontal media diaria. Interactivo - Radiación Website. Available in: http://atlas.ideam.gov.co/visorAtlasRadiacion.html. Last accessed July of 2022.

INIAP (2016). Muestreo foliar en cacao. Plegable no. 429. Availablein: http://repositorio.iniap.gob.ec/handle/41000/3881. Last accessed July of 2022.

Isaac, M.E.; F. Ulzen-Appiah; V.R. Timmer & S.J. Quashie-Sam (2007). Early growth and nutritional response to resource competition in cocoa-shade intercropped systems. Plant and Soil 298(1-2): 243-254.

Lachenaud, P. (1995). Variations in the number of beans per pod in *Theobroma cacao* L. in the Ivory Coast. III. Nutritional factors; cropping effects and the role of boron. Journal of Horticultural Science

70(1): 7-13.

Leiva-Rojas, E. & R. Ramírez-Pisco (2017). Acumulación y extracción de nutrientes en el cultivodel cacao (*Theobroma cacao* L.). International Symposium on Cocoa Research (ISCR). November: 1-7.

León-Moreno, C.E.; J. Rojas-Molina & C.E. Castilla-Campos (2019). Physicochemical characteristics of cacao (*Theobroma cacao* L.) soils in Colombia: Are they adequate to improve productivity? Agronomía Colombiana 37(1): 28-38.

Li, Y.; M. Elson; D. Zhang; Z. He; R. Sicher & V. Baligar (2015). Macro and micronutrient uptake parameters and use efficiency in cacao genotypes as influenced by levels of soil applied K. International Journal of Plant & Soil Science 7(2): 80-90.

López, N.R.E. & S.V.A Lucas (2018). Efecto de la fertilizacion con N, S, micronutrientes y fitorreguladores sobre el rendimiento y rentabilidad del cacao Nacional en el valle del Rio Carrizal. Ing. Thesis. Escuela Superior Politécnica Agropecuaria de Manabí Manuel Félix López. Calceta, Ecuador. pp. 38-54.

Ludeña-Davila, V. (2013). Efecto de la fertilización orgánica y microelementos en el rendimientode cacao CCN51 (*Theobroma cacao* L.) en Jaen. Ingeniería en Conservación de Suelos y Agua. Ing. Thesis. Facultad de recursos naturales renovables. Universidad Nacional Agraria De La Selva. Tingo María, Perú. pp. 26-40.

Maathuis, F.J.M. & E. Diatloff (2013). Roles and Functions of Plant Mineral Nutrients. In: Plant Mineral Nutrients: Methods and Protocols, Methods in Molecular Biology. Frans J.M. Maathuis,Ed. Humana Totowa, NJ. pp. 1-21.

MADR (2021). Cadena de valor de Cacao. Available in: https://sioc.minagricultura.gov.co/Cacao/Documentos/2021-03- 31%20Cifras%20Sectoriales.pdf. Last accessed June of 2022.

Malavolta, E.; G.C. Vitti & S.A. De Oliveira (1997). Avaliação do estado nutricional das plantas. Principios e aplicaçõe. In: Associação Brasileira para Pesquisa da Potassa e do Fosfato (2a edicica). Piracicaba.

Mejia Flórez, L.A. & G. Palencia (2000). Efecto de la nutrición en el cultivo de cacao (*Theobroma cacao* L.) en la zona productora de Santandar. Seminario Técnico Regional 5(5): 30-33.

Mortimer, R.; S. Saj & C. David (2018). Supporting and regulating ecosystem services in cacao agroforestry systems. Agroforestry Systems 92(6): 1639-1657.

Motsara, M.R. & R.N. Roy (2008). Guide to laboratory establishment for plant nutrient analysis. Food And Agriculture Organization of The United Nations Rome, 2008. In Fao Fertilizer and Plant Nutrition Bulletin 19.

N'Guessan, K.; M.J. Traore; D. Snoeck; E. Kassin; L. Koko; M. Camara & A. Yao-kouame (2017). Mapping Cacao Fertiliser Requirements in Côte d'Ivoire. Imperial Journal of Interdisciplinary Research 3(6): 504-515.

Nygren, P. & H.A. Leblanc (2015). Dinitrogen fixation by legume shade trees and direct transferof fixed N to associated cacao in a tropical agroforestry system. Tree Physiology 35(2): 134- 147.

Oberthür, T.; M. Samson; N.Janetski; K. Janetski & M. Fisher (2018). Response of cacao seedlings to fertilizer. Better Crops with Plant Food 102(4): 20-23.

Ofori, A.; F.K Padi; A. Akpertey; P. Adu-Gyamfi; M.A Dadzie & F.M Amoah (2017). Variabilityof survival and yield traits in cacao (*Theobroma cacao* L.) clones under marginal field conditionsin Ghana. Journal of Crop Improvement 31(6): 847-861.

Osorio, W (2012). El análisis foliar: una poderosa herramienta para diagnosticar el estado nutricional de los cultivos; pasturas y plantaciones. Manejo Integral del Suelo y Nutrición Vegetal 1(3): 1-4.

Palencia, G.E.; R. Gómez & O. Gûiza (2009). Nuevas tecnologías para instalar viveros y producir clones de cacao (*Theobroma cacao* L). Corpoica. Available in: http://hdl.handle.net/20.500.12324/2194. Last accessed August of 2022.

Puentes-Páramo, Y; J. Menjivar-Flores; A. Gómez-Carabalí & F. Aranzazu-Hernández (2014a). Absorción y distribución de nutrientes en clones de cacao y sus efectos en el rendimiento. Acta Agronomica 63(2): 145-152.

Puentes-Páramo, Y; J. Menjivar-Flores; F. Aranzazu-Hernández (2014b). Eficiencias en el uso de nitrógeno, fósforo y potasio. Bisagro 26(2): 99-106.

Puentes-Paramo, Y.J.P.; A.G. Carabalí & J.C.M. Flores (2016a). Influence of the relationship among nutrients on yield of cocoa (*Theobroma cacao* L.) clones. Acta Agronomica 65(2): 176-182.

Puentes-Páramo, Y; J. Menjivar-Flores; F. Aranzazu-Hernández (2016b). Concentración de nutrientes en hojas, una herramienta para el diagnóstico nutricional en cacao. Agronomía Mesoamericana 27(2): 329-336.

Quek, R.Y.C.; E.W.Y. Peh & C.J. Henry (2020). Effects of cocoa butter and cocoa butter equivalent in a chocolate confectionery on human blood triglycerides, glucose, and insulin. Foods 9(4): 455.

Reich, M.; T. Aghajanzadeh & L.J. De Kok (2014). Physiological basis of plant nutrient use efficiency-concepts, opportunities and challenges for its improvement. Hawkesford, M., Kopriva, S., De Kok, L., Eds. In: Nutrient Use Efficiency in Plants. Plant Ecophysiology, vol 10.Springer, Cham. pp. 1-28.

Ribeiro, M.A.Q.; J.O. Da Silva; W.M Aitken; R.C.R. Machado & V.C. Baligar (2008). Nitrogenuse efficiency in cacao genotypes. Journal of Plant Nutrition 31(2): 239-249.

Romero; F.C. (2018). Biomass and nutrient distribution in cacao trees (*Theobroma cacao*): A case study in Cote d'Ivoire. M.Sc. Thesis. Wageningen University. Wageningen, Países Bajos.pp.22-38. Available in: https://edepot.wur.nl/501084. Last accessed August of 2022.

Rosas-Patiño, G.; Y.J. Puentes-Páramo & J.C. Menjivar-Flores (2017). Relación entre el pH yla disponibilidad de nutrientes para cacao en un entisol de la Amazonia colombiana. CorpoicaCiencia y Tecnologia Agropecuaria18(3): 529-541.

Rosas-Patiño, G.; Y.J. Puentes-Páramo & J.C. Menjivar-Flores (2019). Efecto del encalado en el uso eficiente de macronutrientes para cacao (*Theobroma cacao* L.) en la Amazonia colombiana. Ciencia y Tecnología Agropecuaria 20(1): 5-16.

Ruales-Mora, J.L.; H. Burbano-Orhuela & W.P. Ballesteros (2011). Efecto de la fertilización con diversas fuentes sobre el rendimiento de cacao (*Theobroma cacao* L.). Revista de Ciencias Agrícolas 28(2): 81-95.

Salvador, N.; E. Espinosa & J.C. Rojas (2012). Manual del cultivo de cacao blanco de Piura. Mesa Técnica Regional de Cacao de Piura. Dirección Regional Agraria Piura; PER. Available in: https://doi.org/http://www.swisscontact.org.pe/ biblioteca-virtual. Last accessed August of 2022.

Sánchez, L.E.; D. Parra; E. Gamboa; & J. Rincón (2005). Rendimiento de una plantación comercial de cacao ante diferentes dosis de fertilización con NPK en el sureste del estado Táchira, Venezuela. Bioagro 17(2): 119-122.

Sánchez, V.; J.L. Zambrano; C. Iglesias; E. Rodríguez; V. Villalobos & F.J. Díaz (2019). La Cadena de Valor del Cacao en América Latina y El Caribe. In La cadena de valor del cacao en América Latina y el Caribe. Available in: http://repositorio.iniap.gob.ec/handle/41000/5382. Last accessed August of 2022.

Santana, M.B.M. & P. Cabala-Rosand (1982). Dynamics of Nitrogen in a Shaded CacaoPlantation. Plant and Soil 67(1/3): 217-281.

Shin, R. (2014). Strategies for improving potassium use efficiency in plants. Molecules and Cells 37(8): 575-584.

Silva, S. de A.; J.S. Lima de S; G.S. Souza; R.B. Oliveira & A.C. Xavier (2010). Lógica fuzzy na avaliação da fertilidade do solo e produtividade do café conilon. Revista Ciencia Agronomica 41(1): 9-17.

Snoeck, D; M.K. Abekoe; A.A Afrifa & M.R. Appiah (2007). The soil diagnostic method to compute fertilizer requirements in cocoa plantations. International Conference on Soil Science Accra; January; 7–11. Available in: https://agritrop.cirad.fr/554340/1/document_554340.pdf. Last accessed October of 2022.

Snoeck, D.; A.A. Afrifa; K. Ofori-Frimpong; E. Boateng & M.K. Abekoe (2010). Mapping fertilizer recommendations for cocoa Production in Ghana using soil diagnostic and GIS tools. West African Journal of Applied Ecology 17(January 2014): 97-107.

Snoeck, D; L. Koko; J. Joffre; P. Bastide & P. Jagoret (2016). Cacao Nutrition and Fertilization. E. Lichtfouse, Eds. In: Sustainable Agriculture Reviews. Sustainable Agriculture Reviews, vol 19. Springer, Cham. 155-202 pp.

Sodre, G.A.; P.C.L. Marrocos; R.E. Chepote & R.G. Pacheco (2001). Uso do desvio padrão para estimativa do tamaño de amostra de plantas de cacau (*Theobroma cacao* L.) em estudosde nutriçao. Agrotropica 145-150.

Sodré, G.A.; P.C.L. Marrocos & R.G. Pacheco (2010). Quality of cocoa plants produced by stem cuttings and transported without substrate. Magistra 22(2):118-121.

Suh, N.N. & E.L. Molua (2022). Cocoa production under climate variability and farm management challenges: Some farmers' perspective. Journal of Agriculture and Food Research 8: 100282.

Thong, K.C. & W.L. Ng (1980). Growth and nutrient composition of mono-crop cocoa plants on inland Malaysian soils. In Proceedings of the International Conference on Cocoa and Coconuts, 1978, Kuala Lumpur: Incorporated Society of Planters. pp: 262-286.

Tuesta-Pinedo, Á.L.; E. Trigozo-Bartra; J.J. Cayotopa-Torres; E. Arévalo-Gardini; C.O. Arévalo-Hernández; L.B. Zúñiga-Cernadez & B. Leon-Ttacca (2017). Optimización de la fertilización orgánica e inorgánica del cacao (*Theobroma cacao* L.) con la inclusión de Tricoderma endófito y Micorrizas arbusculares. Revista Tecnología en Marcha 30(1): 67.

UPRA (2019). Zonificación de Aptitud para el Cultivo Comercial de Cacao. Availablein: https://www.datos.gov.co/Agricultura-y-Desarrollo-Rural/Zonificaci-n-De-Aptitud-Para-El- Cultivo-Comercial-/enap-bk3n. Last accessed October of 2022.

Uribe, A.; H. Méndez & J. Mantilla (1998). Efecto de niveles de nitrógeno, fosforo y potasio enla producción de cacao en Colombia. Suelos Ecuatoriales 28: 31-36.

van Vliet, J.A.; M. Slingerland & K.E. Giller (2015). Mineral Nutrition of Cocoa (Issue July).

van Vliet, J.A.; & K.E. Giller (2017). Mineral Nutrition of Cocoa: A Review. In Advances in Agronomy 141: 185-270.

Wang, M.; Q. Zheng; Q. Shen & S. Guo (2013). The critical role of potassium in plant stress response. International Journal of Molecular Sciences 14(4): 7370-7390.

Wang, Y. & W.H. Wu (2015). Genetic approaches for improvement of the crop potassium acquisition and utilization efficiency. Current Opinion in Plant Biology 25: 46-52.

Wesse, M. (1971). Fertilizer requirements of cacao (*Theobroma cacao* L.) in South-Western Nigeria. In Communication 61. Koninklijk Instituut voor de Tropen.

Wickramasuriya, A.M. & J.M. Dunwell (2018). Cacao biotechnology: current status and future prospects. Plant Biotechnology Journal 16(1): 4-17.

Zarrillo, S.; N. Gaikwad; C. Lanaud; T. Powis; C. Viot; I. Lesur; O. Fouet; X. Argout; E. Guichoux; F. Salin; R.L. Solorzano; O. Bouchez; H. Vignes; P. Severts; J. Hurtado, A. Yepez; L. Grivetti; M. Blake & F. Valdez (2018). The use and domestication of *Theobroma cacao* during the mid-Holocene in the upper Amazon. Nature Ecology and Evolution 2(12): 1879-1888.