OPEN ACCESS
Journal of Agronomy
ISSN 1812-5379
DOI: 10.3923/ja.2018.
CrossMark

Research Article
Physico-chemical Properties of Soil and Pods (*Theobroma cacao* L.) in Cocoa Agroforestry Systems

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Abstract
Objective: This study aimed to characterise the physico-chemical properties of soils and the biochemistry of cocoa pods in cocoa agroforestry systems, that may be beneficial for community of cocoa associations under agroforestry systems in the tropical, Tabasco, Mexico. **Methodology:** Granulometric, biochemical and physical analysis showed that the cocoa agroforestry plantations of the municipal districts of Cunduacán, Cardenas Comalcalco have clayey soils, pH was moderately acidic to neutral and it had high levels of organic matter and total nitrogen content: 9-10 and 0.15-0.21%, respectively. Data were analyzed by linear model and one-way (ANOVA) using SAS. **Results:** The average nutritional content of cocoa pods from cocoa agroforestry systems was as follows, total carbon (94.34%), Zn (50.26%), nitrogen (1.33%), potassium (1.78%), calcium (0.42%), magnesium (0.32%), ash (93.20%) and protein (8.3%). The electrical conductivity was influenced by various physico-chemical properties of the soil, such as soil texture, organic matter content, soil moisture, cation exchange capacity, salinity, pH, Ca and Mg. The physico-chemical properties and high nutritional content of the soils used in these agroforestry systems were suitable for the sustainable production of cocoa. **Conclusion:** It was concluded that results may vary depending on the natural balance between the vegetation habitat and the biochemical, biological, physical and chemical properties of the soil.

Key words: Electrical conductivity, sustainable, cocoa, biochemical, organic matter

Received: Accepted: Published:

Citation: Hortensia Brito-Vega, José Manuel Salaya-Domínguez, Edmundo Gómez-Méndez, Armando Gómez-Vázquez and Jesús Bernardo Antele-Gómez, 2018. Physico-chemical properties of soil and pods (*Theobroma cacao* L.) in cocoa agroforestry systems. J. Agron., CC: CC-CC.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Agroforestry can be defined as a series of systems and technologies to optimise the agricultural use of land where there is a great diversity of flora and fauna and where crops require some shade. Agroforestry involves a series of strategies that allow a sustainable use of land, as in the case of the cultivation of cocoa under shade[1]. However, there is scarce knowledge about the importance of the physicochemical properties of the soil in agroforestry cocoa production, specially about the importance of the quality and availability of soil nutrients. In Mexico, cocoa is grown mainly in association with fruits, legumes, timber and non-timber plants. Cocoa crops form a complex system that can function as a biological corridor and that can provide environmental services such as carbon sequestration and water conservation[2]. Shade trees contribute to the sustainability of this system by producing litter, recycling nutrients and preventing soil erosion[3]. The state of Tabasco is the main producer of cocoa in Mexico, with 70% of total national production, followed by the state of Chiapas, with 29%. The main cocoa producing municipal districts in the state of Tabasco are: Comalcalco (4,797.87 t), Cardenas (4,522.09 t), Cunduacán (3,819.09 t), Huimanguillo (2,687.15 t), Jalpa de Méndez (1,247 t) and Paraíso (665 t)[4]. The shells of cocoa pods are discarded as waste product after the extraction of cocoa pulp. These shells are 52-70% of the wet weight of the fruit, their ash free content of cellulose and hemicellulose is 30 and 35 wt %, respectively[5]. The shells of cocoa pods or the whole fruits are used as fertilizer, composted or applied directly to the soil. Soil surveys are crucial for land management and economic planning in any country. Soil surveys must characterise the physico-chemical properties of soils, their spatial distribution pattern and most importantly, the limitations of each type of soil for the implementation of agricultural and forestry projects[6,7]. The information obtained from these studies allows forestry specialists to develop standards for forest and natural vegetation conservation, the establishment of plantations, the restoration of degraded areas and the selection of potentially suitable areas for the establishment of agroforestry systems[8]. The variety of plants typical of agroforestry systems increases the content of organic matter in the soil, improving the availability of macro and micronutrients assimilable to plants. It also helps to maintain the soil pH at a suitable level for plant development, it increases the recycling capacity of the soil and improves the mobilization of poorly soluble nutrients. Agroforestry soils also have a better structure and better water-holding capacity, they allow for good vegetation cover, reducing erosion and promote the activity of soil microorganisms, which favors the return of phosphorus and potassium to the soil[9]. The aim of this study was to characterise the physico-chemical properties of soils and the biochemistry of cocoa pods in cocoa agroforestry systems.

MATERIALS AND METHODS

Characteristics of the study area: In the municipalities of Cardenas, Cunduacan and Comalcalco municipalities of Tabasco, Mexico were carried out in the year 2013-2015.The state of Tabasco is located in Southeastern Mexico, it has 191 km of coast (1.58% of the country's coast). It is bordered on the North by the Gulf of Mexico, on the Northeast by the state of Campeche, on the Southeast by the Republic of Guatemala, on the West by the state of Veracruz and on the South by Chiapas. Its surface covers an area of nearly 25,000 km^2. Within the state, the Chontalpa region, the second largest, occupies 7,482.13 km^2, (31.34% of the Tabasco territory), it has 593,668 inhabitants, of whom 241,168 live in urban areas and 352,500 in rural areas. Chontalpa contains three municipal districts with cocoa agroforestry systems, Comalcalco, Cardenas and Cunduacán (Table 1). The Chontalpa region is located between 17°59' N and 91°32' W, at an altitude of 2-17 masl, its climate is warm and humid, with annual and monthly rainfall of 2,643 and 355 mm, respectively and an average annual temperature of 26°C and a maximum of 45°C[10]. The soils of the cocoa agroforestry systems of Chontalpa are Eutric Fluvisols (Fleu) and Eutri-Gleyic Fluvisols (Flugel), which are representative of the region[10].

Collection of samples: Sampling was conducted in three stages: (1) Collection of soil, foliar and fruit samples in the farms of the study area, (2) Chemical analysis of the samples in the soil analysis laboratory of the Colegio de Postgraduados, Campus Tabasco, (3) Statistical analysis and interpretation of results. Four samples were taken in each of the three municipal districts under study (Comalcalco, Cardenas and Cunduacán), for a total of 12 composite soil samples, each formed by 30 random homogeneous horizon (0-30 cm depth) subsamples. The soil samples were air dried and sieved through a 2 mm mesh[11]. Physico-chemical characterization of soil, granulometric analysis, pH, electrical conductivity, bulk density, organic matter, nitrogen, carbon, calcium, phosphorus and potassium.

Leaf and pod samples must be collected from specific parts of the plant and at a specific growth stage to correctly interpret the test results. The collected leaves and pods were healthy, without mechanical lesions and were recently

Table 1: Location of sampling sites in the municipalities of Tabasco under agroforestry systems cacao plantations

Municipality	Location	Coordinates
Cunduacán	Yoloxochitl 1ra sección	18°06'16.9"N 93°16'50.2"W
Cunduacán	Miahuatlan	18°06'07.7"N 93°09'54.2"W
Cunduacán	San Severo	18°08'05.5"N 93°07'48.9"W
Cunduacán	Yoloxochitl 2da sección	18°04'55.7"N 93°15'06.4"W
Comalcalco.	Oriente 3ra sección	18°18'38.3"N 93°13'01.5"W
Comalcalco	Oriente 2da sección	18°18'54.3"N 93°12'37.0"W
Comalcalco	Chipilín	18°19'03.8"N 93°13'24.4"W
Comalcalco	Benito Juárez	18°18'43.6"N 93°12'54.7"W
Cárdenas	Arroyo hondo 2°sección	18°01'37.2"N 93°25'01.5"W
Cárdenas	Poblado C-28	17°59'33.1"N 93°20'53.4"W
Cárdenas	Arroyo hondo 1ra sección	18°01'01.0"N 93°26'11.5"W
Cárdenas	Poblado C-31	17°59'33.2"N 93°20'55.2"W

physiologically mature, they were collected from the middle of the branches of the year. The collected shoots were not pendular shaped or sucker shoots[5]. The collected leaves were external and were found at a medium altitude of 1.5-2.5 m, all had petiole. The composite sample contained between 50 and 100 leaves, with a total dry weight of about 100 g. Three pods were collected from each plant for a total of 30 pods.

Proximate analysis: A proximate analysis was performed to determine, moisture (H), ashes (Cz), ether extract (EE), total carbohydrates (CHOs), crude protein (PrCF), total sugars (AzT) and pH[12]. The quantification of each compound was done in triplicate and the results were expressed in g (parameter)/100 g (dry sample).

Statistical analysis: The data was analyzed by linear model and one-way ANOVA ($p<0.05$)[13]. An analysis of Pearson correlation coefficients between pairs of variables was also performed using SAS statistical software, all rights reserved. Produced in the United States of America[14]. All treatments were conducted in triplicates and the mean values reported.

RESULTS AND DISCUSSION

Physicochemical characterization of soil: Granulometric analysis showed that the cocoa agroforestry plantations of the municipal districts of Cunduacán, Cardenas Comalcalco have clayey soils (25% sand, 25% silt and 50% clay) (Table 2). Other studies have reported that agroforestry cocoa systems are established on silty and clay loam soils[9], these type of soil textures provide moderate to adequate infiltration and only a small portion are poorly drained soils. Clayey soils predominate in the 12 sites studied here. The soils under study may take over 1000 years to change even under agricultural exploitation[15,16], soil texture influence the dynamics of soil organic matter (OM), which increases in clayey soils, there was a positive relationship between the proportion of clay in the soil and the content of organic matter in agroforestry systems[17]. Soil pH is moderately acid (5.6) to neutral (6.9) in Cunduacán, Cardenas and Comalcalco (Table 2). This indicates that the soils have adequately balanced nutrient levels and have great potential for agricultural use[9, 7]. The average bulk density of the soils was 1.19 g cc^{-1} in the 12 study sites, with minimum values of 1.06 g cc^{-1} and maximum values of 1.43 g cc^{-1}. Cocoa agroforestry systems use minimum tillage, which does not affect bulk density (Da). Peaty soils can have bulk density values lower than 0.25 g cc^{-1}, while compacted soils can have values higher than 1.90 g cc^{-1}, in volcanic mineral soils, bulk density is close to 0.85 g cc^{-1}[18]. That well structured clayey soils with high organic matter content have bulk density values of 1.0-1.30 g mL^{-1}, while sandy soils with low organic matter content have high bulk density values of 1.50-1.70 g mL^{-1}[19]. Table 3 shows the correlation coefficient between organic matter content and soil bulk density in cocoa

Table 2: Correlation matrix of the physico-chemical properties of soils of cocoa agroforestry systems

Variables	Numbers	Media	Typical	Sum	Minimum	Maximum
pH	12	6.21667	0.38808	74.60	5.60	6.90
Da (g cc^{-1})	12	1.19166	0.33090	14.30	1.06	1.43
EC (dSm^{-1})	12	0.28083	0.33535	3.37	0.07	0.90
OM (%)	12	9.33333	0.49237	112.00	9.00	10.00
Nt (%)	12	0.17583	0.02429	2.11	0.15	0.21
P (mg Kg^{-1})	12	15.2800	7.08372	183.36	6.83	34.58
K (cmol (+) g kg^{-1})	12	0.34917	0.16127	4.19	0.20	0.79
Ca (cmol (+) g kg^{-1})	12	17.8125	4.82239	213.75	11.80	25.91
Sand (%)	12	24.6666	6.62411	296.00	20.00	40.00
Silt (%)	12	25.1666	19.47415	302.00	4.00	60.00
Clay (%)	12	50.1666	21.49771	602.00	14.00	72.00

Da: Tillage , EC: Electrical conductivity, OM: Organic matter, Nt: Nitrogen content, P: Phosphorus, K: Potassium, Ca: Calcium

Table 3: Correlation coefficients of the chemical-physical characterization of the agrosystem cacao soils

Variables	pH	EC (dSm^{-1})	OM (%)	Nt (%)	P (mg kg^{-1})	Da (g cc^{-1})
pH	1.00000	0.00268	0.30132	-0.12696	-0.22527	-0.30229
EC (dSm^{-1})		1.00000	0.02019	-0.11559	-0.12947	-0.22527
Da (g cc^{-1})			1.00000	0.02019	-0.11559	-0.12947
OM (%)				1.00000	0.32935	-0.29662

Pearson correlation coefficients, Number of samples = 12, Prob> |r| Assuming H0: Rho: 0, Da: Tillage , EC: Electrical conductivity, OM: Organic matter, Nt: Nitrogen content, P: Phosphorus

agroforestry systems. There were no significant differences between both properties. The organic matter content is a key factor that reduces the bulk density of the soil, improving aggregate stability and favoring a porous structure[15]. The submitted to a range of matric suction for which soil bulk density (BD), the S-value of 0.035 for conventional crop management indicates that this management was unable to maintain soil physical quality on the same levels as agroforestry systems and natural vegetation[20]. The decrease of the least limiting water range (LLWR) with BD occurred for all treatments and the BD at a maximum effect (LLWR = 0) which is called the critical BD (BDc), was, respectively, 1.69, 1.62, 1.56 and 1.56 Mg m^{-2} for agroforestry systems (agrosilvipasture and silvipasture), conventional crop management and natural vegetation have been maintained.

The electrical conductivity (EC) of the soil samples taken from cocoa agroforestry systems ranged from 0.07-0.90 dSm^{-1}. EC is influenced by various physico-chemical properties of the soil, such as soil texture, organic matter content, soil moisture, cation exchange capacity, salinity, pH, Ca and Mg, among others[21]. EC is a potential indicator of the spatial variability of clay and moisture content in the soil. The clay content is stable over time and it is associated with the moisture content, affecting the growth and development of crops[21].

The soils of the cocoa agroforestry systems studied here had organic matter content values of 9-10%, as can be seen in the correlation matrix of the physico-chemical properties of soils of cocoa agroforestry systems (Table 2 and 3). This was explained because these systems provide large amounts of organic waste (vegetable scraps of cocoa pods and forest litter), which mineralize very slowly and accumulate in the soil surface. Organic matter (OM) is closely related with plant remains and the type of vegetation influences the quality and content of soil organic matter. Cedar-banana agroforestry systems, for example, conserve soil OM content throughout the year[22]. Assessing the spatial variability of soil organic carbon (SOC) is crucial for SOC monitoring and comparing management options. Local variability of SOC in this volcanic agroforestry watershed was dominated by andic properties whereas topographic or vegetation variables had very little impact. Estimation of SOC variability is recommended using inexpensive proxy measurements like VNIRS (visible-near-infrared reflectance spectroscopy) (RMSE = 12.3 g kg^{-1}) rather than spatial interpolation techniques[23].

Regarding nitrogen content (Nt), the soils under study showed values of 0.15-0.21% (Table 2 and 3). The ability of some systems to retain atmospheric nitrogen is associated with the type of vegetation, the history of land use, topography and soil conditions. The nitrogen content of ecosystems depends on the loss of anions and cations from the soil, acidification processes increase the loss of nitrogen from the systems[24].

The content of phosphorus (P) showed significant differences between the soils of three districts under study, ranging from 6.83-34.58 mg kg^{-1} (Table 2). These values are considered adequate for cocoa agroforestry systems[9]. An adequate content of phosphorous benefits the plants because most absorbing roots, responsible for assimilating P, are found in the first soil horizon. The low mobility of soil P minimises the risk of leaching into the groundwater[25].

Table 4: Matrix of nutritional correlation of cocoa pods under cocoa agroforestry systems

Variables (%)	Numbers	Media	Typical	Sum	Minimum	Maximum
Total carbon	12	93.22	0.65	1119.00	92.30	94.34
N	12	1.33	0.18	16.00	1.03	1.63
P	12	0.27	0.02	3.25	0.23	0.31
K	12	1.78	0.06	21.41	1.68	1.91
Ca	12	0.42	0.10	5.08	0.28	0.58
Mg	12	0.32	0.05	3.89	0.25	0.43
Cu	12	12.92	4.60	155.05	5.38	20.21
Zn	12	38.14	5.89	457.68	26.72	50.26

The content of potassium (K) showed significant differences between the soils of three districts under study, ranging from (0.20-0.79 mg kg^{-1}) (Table 2). Cocoa crops demand high quantities of potassium due to its participation in the synthesis of carbohydrates[26]. The high content of K in these soils is associated with the transformation and integration of organic matter and these systems provide many plant residues that are integrated to the soil. However, the availability of this element depends on soil texture, clay soils have higher amounts than sandy soils[27]. This is consistent with findings by soil fertility and soil organic matter (SOM) dynamics under QSMAS and SB agriculture, with secondary forest (SF) as a reference. However, the significant interaction between cropping system and fertilizer application observed in this study indicates that 4 within plots receiving fertilizer additions, P was more available under QSMAS compared to SB management. Although inputs of organic P (as applied residues) may contribute to P availability in the QSMAS system, there was no difference between unfertilized QSMAS vs. SB plots, thus suggesting that the greater increase in available P with fertilization in the QSMAS system was due to other factors[28].

The content of calcium (Ca) showed significant differences between the soils of the three districts under study, ranging from 11.80-25.91 mg kg^{-1} (Table 2 and 3). Calcium, which is hydrophobic, absorbed by plants in its ionic forms from the soil solution. The relative concentration of this element determines root turgor (pressure against the cell walls) and osmotic pressure, when the two pressures are equalized, the cell does not win or lose water[29].

With the assessing variations in selected soil properties, two tillage types: Agroforestry based conservation tillage (AFCST) and maize based conventional tillage (MCVT) under three age categories (5, 10 and 15 years) were selected in Chichu and Haroresa Kebels, Dilla Zuria, Ethiopia. Soil bulk density, soil moisture content (SMC), total porosity (Pt) and soil organic carbon (SOC) varied significantly with tillage types ($p<0.001$) and soil depth ($p<0.001$). Water infiltration (rate and cumulative) significantly varied ($p<0.001$) with tillage types, Higher in the AFCST than in the MCVT. Lower soil bulk density, higher soil organic carbon (SOC) and soil moisture content (SMC) were observed in the top 0-10 cm soil layer under the AFCST than in the MCVT. Soil bulk density and soil moisture content (SMC) increased while total porosity (Pt) and soil organic carbon (SOC) decreased with soil depth in both tillage types[30]. The variation in species composition among agroforests contributed to a greater γ-diversity than α-diversity. Monthly average maximum temperatures were approximately 6°C higher in full-sun coffee than in agroforests and forests[31]. Cocoa-coconut agroforestry also had the highest organic carbon and soil organic matter, conditions supporting the growth and activity of beneficial soil microbes (*Pseudomonas* sp. and *Trichoderma* sp.). In addition, total land equivalent ratio of cocoa-coconut agroforestry had the highest value at 1.36, indicating a highest yield advantage was gained. Therefore, cocoa-coconut agroforestry could be a wise option to promote environmental sustainability of cocoa cultivation[32].

Physical and biochemical parameters of cocoa: Table 4 shows the results of the correlation matrix of the nutrients of cocoa pods grown under cocoa agroforestry systems. Carbon (94.34%) and Zinc (50.26%) were present in high amounts, unlike the other compounds. Fresh cocoa pods are made up mainly of carbon but the content of this compound is significantly different between the three cocoa varieties, Criollo, Forastero and Trinitario. The Forastero variety had the lowest concentration of carbon, the Trinitario variety had the highest concentration[33]. Other important compounds found in cocoa pods are nitrogen (1.33%), potassium (1.78%), calcium (0.42%), magnesium (0.32%), copper and zinc (Table 4). These compounds are involved in biochemical reactions that occur during the transformation and degradation of the pods into soil organic waste[33]. The average ash content of cocoa pods was 93.20%, with a minimum of 92.30% and a maximum of 94.24% (Table 5). Ash content refers to the inorganic residue left after ignition or complete oxidation of organic matter in a foodstuff. The maximum protein content in the cocoa pods studied here was 10.22% (Table 5), which contrasts with the results, who found protein

Table 5: Correlation of the bromatological analysis of the cocoa ear under agroforestry cacao systems

Variables (%)	Numbers	Media	Typical	Sum	Minimum	Maximum
Protein	12	8.33	1.18	100.03	6.45	10.22
Ashes	12	93.20	0.64	1118.00	92.30	94.24
Moisture	12	81.72	3.35	980.71	77.78	90.00
Fatty	12	1.48	-	17.76	1.48	1.48

Table 6: Proximal analysis of the cocoa ear under agroforestry cacao systems

Sitio	pH	CHOS (%)	AzT (%)	EE (%)
Cárdenas	6.02^{a}	32.61^{abc}	2.76^{de}	49.88^{cd}
Comalcalco	5.97^{d}	32.00^{abc}	2.68^{cd}	47.32^{def}
Cunduacán	5.94^{cd}	33.33^{a}	2.66^{cd}	49.45^{f}

Different letters in the same column indicate significant differences ($p<0.005$) according to Tukey test, Total carbohydrates (CHOs), Total sugars (AzT), Ether extract (EE)

content values of 14.7-20.5% protein, this difference may be explained by the pathogenic organisms associated with the pods[34]. The maturity of the pods affects their content of protein and fat[35]. The fat content of cocoa beans and the proportion of fatty acids was constant in the cocoa pods studied here after 5 months.

That farmers cacao should rely more on agroforestry to improve their food security and cash income generation. Land use and land right policies, which currently discourage production cacao from growing tress on their lands, should be revised, so as to give more incentive to them to adopt ecologically and economically more sustainable land use practices tropical[36, 37].

Proximal analysis of the cocoa ear under agroforestry-cacao systems (Table 6), the pH statistically there is a significant difference between Cardenas (6.02), unlike Comalcalco and Cunduacan (5.97 and 5.94), respectively. Cunduacan the CHOs (33.33%) and the EE (49.45%) there is a small significant difference, to different from Cardenas and Comalcalco. The three sites there is no significant difference in AzT. The physical qualities of the beans were analyzed for their proportions of cocoa nibs, shells and germ. Fermentation and increasing pod storage resulted in significant ($p<0.05$) decreases in ash (3.48-2.92%), protein (21.63-17.62%) and fat (55.21-50.40%) content of the beans while carbohydrate content increased from 15.47-24.93% with both treatments. As well, increasing pod storage and fermentation significantly ($p<0.05$) increased the copper content of the beans from while reductions in Mg and K occurred. Amongst the minerals studied, potassium was the most abundant mineral followed by magnesium, phosphorus and calcium in the fermented cocoa beans[5].

CONCLUSION

The soils of cocoa agroforestry systems in the municipal districts of Cardenas, Comalcalco and Cunduacán have a high nutritional content and are suitable for the production of cocoa, agriculture and forestry. The leaves of cocoa plants showed no deficiency of N and P during fruit production. The shells of cocoa pods contain nutrients that are incorporated into the soil after the shells are discarded during harvest and undergo a process of biological and chemical degradation.

SIGNIFICANCE STATEMENT

This study discover the soil fertility level and nutrition of cacao agrosystems that can be beneficial for cocoa producers and to the production of agroforestry systems. This study help the researchers to uncover the critical areas of the conservation and management of organic and inorganic fertility, soil biology and plant nutrition, that many researchers were not able to explore. This study discovers the possible nutritional and fertility status of agroforestry systems that can be beneficial for an adequate management of fertility doses in the plantation and the reduction of production costs in the tropic.

ACKNOWLEDGMENT

To the University Juarez Autonomous of Tabasco for the Financing of the Research Project with key UJAT2012-IB-22 and the Division Academica de Ciencias Agropecuarias for the facilities and support to carry out the investigation.

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