Cacao quality index for cacao agroecosystems in Bahia, Brazil

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\textbf{ABSTRACT}

Brazil is increasingly committed to developing research on the quality of cacao. The objective of this work was to develop a new Cacao Quality Index (CQI) methodology with cacao industry, chocolate flavor, human health and food safety functions, and to show its results in different cacao agroecosystems from the humid region of Bahia. The typical Dystrophic Red-Yellow Argisol, in the cabruca cropping system with 35 shade trees per hectare, reached the highest CQI score. The lowest score obtained from the quality index cacao corresponded to the site characterized by the abrupt Dystrophic Red-Yellow Argisol, in the cabruca cropping system with 60 shade trees per hectare. All cropping sites obtained CQI values between 0.54 and 0.69 and were therefore classified as a regular index. The primary indicators that determined the differences between the highest and lowest CQI score were proteins, total free amino acids, simple carbohydrates (sucrose, fructose and glucose), total acidity, cadmium and barium.

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\section*{Introduction}

Cacao is the fruit of cacao tree (\textit{Theobroma cacao} \textit{L.}), is cultivated over 10 million ha of land area in the tropical countries with world production over 4 million tones\textsuperscript{1}. The cacao beans are raw materials for chocolate, one of the most consumed foods in the world\textsuperscript{2}. Demand for cacao beans is increasing in the world.\textsuperscript{1,3} Farming practices applied by cacao farmers at the beginning of the chocolate supply chain strongly influence several quality parameters of the finished chocolate.\textsuperscript{4} Therefore, the geographic evaluation of the raw material and in its supply chain is one of the tools indispensable to the make cacao sustainable traceable.\textsuperscript{5} For example, cacao bean origin is the most important factor that determining the aroma of all cacao products\textsuperscript{6}; likewise, the differences between cacao varieties and geographical region influence total phenolic contents\textsuperscript{7} and volatile compounds.\textsuperscript{8} Both the mineral\textsuperscript{9} and the biochemical composition\textsuperscript{10} in the dry cacao beans, show differences between soil types and cropping systems.

The research studies have developed standards for aspects of cacao quality that meet industrial criteria as well as international import and export legislation that is aimed for food security.\textsuperscript{11} Some chemical attributes of cacao beans were selected as important quality indicators: pH and total acidity, organic acids (acetic and lactic acids), simple carbohydrates (sucrose, fructose and glucose), lipids, proteins and amino acids, purine alkaloids (theobromine and caffeine) and phenolic substances (catechin, epicatechin), total phenols, minerals elements (nutrients and potentially toxic elements) and mycotoxins.\textsuperscript{11} In this context arose the Cacao Quality Index (CQI) with the purpose of
systematize a large number of chemical attributes of cacao beans in functions able to reflect the main needs of the market of this commodity.\textsuperscript{[12]}

In the initial proposal,\textsuperscript{[12]} CQI is composed of three functions: for the interest of Cacao Industry (I), for the interest of Flavor of the Chocolate (II), for the interest of Medicine/Human health/Food security (III). The variables were deduced numerically from scientific and analytical methods and, accordingly, were interpreted together in a system of information related to cacao quality.\textsuperscript{[12]} The objective of this study was to establish a new CQI according to the chemical quality criteria for dry beans, adapting and creating functions with more indicators related to the agricultural, food and environmental realities in the humid region of Bahia. In this region, this study evaluated the CQI for different cropping sites with different soils and cultivation systems of cacao.

**Materials and methods**

**Cacao quality index**

**Study sites and sampling**

To determine CQI were selected twelve study sites located in the humid zone of the cacao region of Bahia, Brazil (Table 1) whose the Thornthwaite climatic classification corresponds to B4r A’, B3r A’, B2r A’, B2r B’, B1r A’, B1r’ A’, B1w A’. These sites (Table 1) were planted with PH-16 cacao clone under different cropping systems, with a range of shade tree densities and across three soil classes: Argisols, Cambisols and Latosols.

| Cropping Site | Geographic Coordinates | Soil Classification according to SiBCS\textsuperscript{a} | Soil Taxonomy\textsuperscript{b} | Cropping Systems | Average density of shade trees ha\textsuperscript{-1} | Grafs age (years) |
|---------------|------------------------|----------------------------------------------------------|----------------------------------|-----------------|-------------------------------|------------------|
| 1             | 13º 40’ 30” S, 39º 14’ 27” W | cambisolic Dystrophic Yellow Latosol (LAd cam) | Hapludox | Cxr\textsuperscript{c} | 150 | 3 |
| 2             | 13º 44’ 38” S, 39º 30’ 10” W | typic Dystrophic Red-Yellow Argisol (PVAd) | Hapludult | CxE\textsuperscript{d} | 60 | 8 |
| 3             | 13º 45’ 21” S, 39º 20’ 25” W | abrupt Dystrophic Red-Yellow Argisol (PVAd) | Hapludult | Cabruca\textsuperscript{e} | 60 | 4 |
| 4             | 13º 46’ 07.0” S, 39º 17’ 52.0”W | typical Dystrophic Yellow Latosol (LAd) | Hapludox | Typic Hapludox | Cxr\textsuperscript{c} | 350 | 3 |
| 5             | 13º 51’ 08” S, 39º 17’ 54” W | typical Dystrophic Red-Yellow Latosol (LVAd) | Hapludox | Hapludalf | Cabruca\textsuperscript{e} | 400 | 3 |
| 6             | 14º 31’ 14’ S, 39º 15’ 45” W | typical Dystrophic Eutrophic Red-Yellow Argisol (PVAd) | Hapludox | Dystropept | Cabruca\textsuperscript{e} | 35 | 3 |
| 7             | 14º 51’ 36’ S, 39º 14’ 42” W | typical Dystrophic Haplic Cambisol (CXd) | Hapludox | Cabruca\textsuperscript{e} | 70 | 9 |
| 8             | 14º 51’ 47” S, 39º 06’ 47” W | argisolic Dystrophic Red-Yellow Latosol (LVAd arg) | Hapludox | Cabruca\textsuperscript{e} | 35 | 5 |
| 9             | 15º 17’ 04” S, 39º 28’ 43” W | latosolic Dystrophic Yellow Argisol (PAd lat) | Hapludult | Cabruca\textsuperscript{e} | 35 | 3 |
| 10            | 15º 23’ 08” S, 39º 26’ 04” W | typical Dystrophic Red-Yellow Argisol (PVAd) | Hapludult | Cabruca\textsuperscript{e} | 35 | 3 |
| 11            | 15º 23’ 15” S, 39º 25’ 48.6” W | typical Altic Red-Yellow Argisol (PVA al) | Hapludult | Cabruca\textsuperscript{e} | 35 | 3 |
| 12            | 16º 29’ 02” S, 39º 23’ 56” W | abrupt Cohesive Dystrophic Red-Yellow Argisol (PVAd coe) | Hapludox | Cxr\textsuperscript{c} | 400 | 6 |

\textsuperscript{a}Brazilian System of Soil Classification.\textsuperscript{[13]}

\textsuperscript{b}Soil Survey Staff.\textsuperscript{[14]}

\textsuperscript{c}Intercropping with cacao (*Theobroma cacao* L.) and rubber tree (*Hevea brasiliensis* (Willd. Ex Adr de Juss.) Muell. Arg.).

\textsuperscript{d}Cacao with shade of erytrina (*Erythrina fusca* Lour).

\textsuperscript{e}Cabruca is an ecological system of agroforestry cultivation where cacao trees are grown under native trees of the Atlantic Forest of South of Bahia.\textsuperscript{[15]}
Each study site with approximately one hectare was subdivided into three collection areas, characterized by the same soil type and cropping site. Each single sample (three for study site) corresponds to 50 mature cacao pods, for the post-harvest processing of fermentation and drying, completely described in the works of Loureiro et al.\textsuperscript{16} and Loureiro et al.\textsuperscript{17} Cacao sampling occurred on November of 2008. This month was chosen because it is representative of the second harvest period (August 2008 to January 2009).

**Database**

The database used to determine the CQI comes from two previous scientific publications that bring together two main groups of 28 cacao quality indicators: biochemical attributes\textsuperscript{10} and composition of mineral elements.\textsuperscript{9}

The cacao beans biochemical attributes pH, total acidity (meq NaOH 100 g\textsuperscript{-1}), acetic acid (mg g\textsuperscript{-1}), lactic acid (mg g\textsuperscript{-1}), fructose (mg g\textsuperscript{-1}), sucrose (mg g\textsuperscript{-1}), glucose (mg g\textsuperscript{-1}), lipids (g kg\textsuperscript{-1}), proteins (g kg\textsuperscript{-1}), amino acids (mg g\textsuperscript{-1}), catechin (mg g\textsuperscript{-1}), epicatechin (mg g\textsuperscript{-1}), total phenols (mg g\textsuperscript{-1}), theobromine (mg g\textsuperscript{-1}), caffeine (mg g\textsuperscript{-1}) were fully described in the work of Araujo et al.\textsuperscript{10}

The cacao beans composition of mineral elements nitrogen (g kg\textsuperscript{-1}), phosphorus (g kg\textsuperscript{-1}), potassium (g kg\textsuperscript{-1}), calcium (g kg\textsuperscript{-1}), magnesium (g kg\textsuperscript{-1}), silicon (g kg\textsuperscript{-1}), iron (mg kg\textsuperscript{-1}), zinc (mg kg\textsuperscript{-1}), copper (mg kg\textsuperscript{-1}), manganese (mg kg\textsuperscript{-1}), barium (mg kg\textsuperscript{-1}), cadmium (mg kg\textsuperscript{-1}), lead (mg kg\textsuperscript{-1}) were fully described in the work of Araujo et al.\textsuperscript{9}

**Standardized scoring of quality indicators**

The quality indicators were standardized for scores ranging from 0 to 1, according to the function of Wymore\textsuperscript{18}: 

\[
v = \frac{1}{1 + \frac{B}{L} S B + L x - 2L} \quad (1)
\]

In Equation 1, \(v\) is the standardized score; \(B\) is the critical or baseline value of the indicator, whose standard score is 0.5; \(L\) is the lower limit or the lowest value of the indicator, which can be equal to zero; \(S\) is the slope of the tangent of the curve at the base limit or the critical value of the indicator; \(x\) is the original value of the analyzed indicator (attribute). The slope of the tangent (S) was calculated according to Equation 2:

\[
S = \frac{\log(\frac{1}{v}) - 1}{\log(\frac{B - L}{x - L}) \times 2(B + x - 2L)} \quad (2)
\]

To quantify relationships between cacao quality indicators and cacao quality functions, were selected three standardized scoring functions (SSF) types to normalize indicator data (Figure 1). Numerical values for each soil quality indicator were converted into unit less scores ranging from 0 to 1 according to the standardization of equation two (2). As shown in Figure 1, the scoring functions were: (a) "more is better" for scoring curve for positive slopes, (b) 'Less is better' for curve for negative slopes, (c) 'Optimum' curve when a positive curve is reflected at the upper threshold value.\textsuperscript{12}

**Mathematical model**

This CQI has an additive model, consisting of main functions representing the aspects to be evaluated and the quality indicators associated with them, attributes that have weights in accordance with the criteria adopted in the research.\textsuperscript{19} According to this additive model, each function was established as the following equations:

\[
Q_{FPr} = I_1(W_1) + I_2(W_2) + \cdots + I_n(W_n) \quad (3)
\]
In Equation 3, \( Q_{PFn} \) is the principal function quality (PF) of the index; \( I \) refers to the standardized scores of quality indicators related to each PF; \( W \) refers to the weights related to each indicator or principal function. In Equation 4, \( CQI \) is the cacao quality index that integrates all functions. Considering that all the indicators reach the ideal values, the sum of the weights of all the main functions should result in the value 1.0 (one).

\[
CQI = Q_{PF1}(W_{PF1}) + Q_{PF2}(W_{PF2}) + \cdots + Q_{PFn}(W_{PFn})
\]  

Critical limits of the CQI indicators
The quality functions for CQI were cacao industry (CIF), chocolate flavor (CFF), human health (HHF) and food safety (FSF) (Tables 2 and 3).

Performance of the CQI and its functions
The CQI functions consist of simultaneous evaluations after defining the behavior of the indicators (curve type) and distribution of their weights (Tables 2 and 3). The CQI is the sum of the individual...
Table 2. Summary of spreadsheets of the cacao quality index of cropping site characterized by typic Dystrophic Red-Yellow Argisol located in humid region of Bahia, Brazil.

| Function (Weight) | Primary Indicator (Weight) | Secondary Indicator (Weight) | Sample Observation 1 (CQI = 0.64) | Sample Observation 2 (CQI = 0.67) | Sample Observation 3 (CQI = 0.77) |
|-------------------|---------------------------|-----------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| CIFa              | Lipids (0.40)             |                              | 370.58 0.05 0.02 3.23 0.12 18.83 | 348.19 0.0 0.3 0.12 17.58        | 385.19 0.18 0.07 11.26 0.13 17.09 |
|                   | pH (0.25)                 |                              | 5.94 1 0.25 41.53                 | 5.85 1 0.25 42.5                 | 5.96 1 0.25 38.11                 |
|                   | Total Acidity (0.25)      |                              | 13.15 0.99 0.25 41.15             | 13.04 0.99 0.25 41.9             | 14.37 0.93 0.23 35.41             |
|                   | Total Phenols (0.10)      |                              | 45.99 0.85 0.8 14.1               | 47.62 0.9 0.09 15.3              | 62.5 1 0.1 15.23                  |
|                    | Protons (0.10)           |                              | 155.11 0.27 0.03 4.86 0.17 26.35  | 157.08 0.01 0.15 0.15 22.88      | 179.28 0.98 0.1 12.66 0.23 30.28  |
|                    | Total Free Amino Acids (0.20) |                         | 13.05 0.12 0.02 4.39              | 8.5 0 0.03                       | 15.57 0.64 0.13 16.5              |
|                    | Total Phenols (0.20)      |                              | 45.99 0.85 0.17 30.22             | 47.62 0.9 0.18 35.28             | 62.5 1 0.2 25.79                  |
|                    | Simple Carbohydrate -0.15 |                              | Sucrose (0.20) 9.13 0 0.09 16.88  | 12.2 1 0.12 23.5                 | 0.95 0 0.11 14.06                 |
|                    | Fructose (0.40)          |                              | 5.64 0.63                        | 7.02 1                           | 5.96 0.4 11.26                    |
|                    | Glucose (0.40)           |                              | 3.71 0.95                        | 4.77 1                           | 3.41 0.84                        |
|                    | Purine Alkaloids -0.15    |                              | Theobromine (0.70) 30.97 0.01 0.05 8.21 | 28.28 0.03 0.01 2.72          | 28.89 0.03 0.05 6.16              |
|                    | caffeine (0.30)          |                              | 4.9 1                           | 6.18 0.23                        | 4.85 1                           |
|                    | Total Acidity (0.10)     |                              | 13.15 0.99 0.1 17.64             | 13.04 0.99 0.1 19.32             | 14.37 0.93 0 11.99                |
|                    | Organic Acids -0.1        |                              | Acetic Acid (0.60) 9.93 1 0.1 17.8 | 1.71 0.95 0.1 19                  | 1.33 1 0 12.85                    |
|                    | Lactic Acid (0.40)       |                              | 0.48 1                          | 0.72 1                           | 0.96 0.99                        |
| HHFb               | Phenolic Substances -0.3 |                              | Epicatechin (0.70) 4.42 1 0.23 34.5 0.2 30.95 | 3.62 1 0.25 37.98 0.2 29.97       | 4.69 1 0.22 32.49 0.21 26.72       |
|                    | Catechin (0.30)          |                              | 1.65 0.2                          | 1.99 1                           | 1.54 0.13                        |
|                    | Theobromine (0.70)       |                              | 30.97 0.01 0.06 9.32             | 28.28 0.03 0.02 2.77             | 28.89 0.03 0.06 9.31              |
|                    | caffeine (0.30)          |                              | 4.9 1                           | 6.18 0.23                        | 4.85 1                           |
|                    | Macronutrients -0.2      |                              | N (0.20) 2.48 0.94 0.17 26.47     | 2.19 0.47 0.16 23.47             | 2.87 1 0.16 23.83                 |
|                    | P (0.30)                 |                              | 2.79 1                          | 2.83 1                           | 2.41 0.89                        |
|                    | K (0.20)                 |                              | 8.99 1                          | 8.87 1                           | 8.07 1                           |
|                    | Ca (0.10)                |                              | 2.77 0.99                       | 2.77 0.99                        | 2.7 0.98                         |
|                    | Mg (0.10)                |                              | 2.18 0.86                       | 2.13 0.79                        | 1.99 0.48                        |
|                    | Si (0.10)                |                              | 0.4                            | 1.2 0.12                         | 0.8 0.01                         |
|                    | Micronutrients -0.2      |                              | Fe (0.40) 27.92 1 0.12 18.13    | 92.02 1 0.14 20.98               | 33.88 1 0.14 19.82               |
|                    | Zn (0.40)                |                              | 29.99 0.5                       | 32.23 0.75                       | 31.63 0.69                      |
|                    | Mn (0.20)                |                              | 16.25 0                         | 14.0 0                           | 13.7 0                          |
|                    | Potentially Toxic Elements (0.10) |             | Cd (0.30) 0.4 0.22 0.08 11.57 | 0.2 0.98 0.1 14.79               | 0.1 0 1 14.55                    |
|                    | Pb (0.30)                |                              | 0.1                            | 0.98 0.1                         | 0.1 0                           |
|                    | Ba (0.20)                |                              | 2.5 0.98                       | 2.8 0.97                         | 2.7 0.98                        |
|                    | Cu (0.20)                |                              | 25.8 1                         | 24.1 1                           | 22.7 0.99                      |
|                    | FSFd                    |                              | Cd (0.30) 0.4 0.22 0.07 11.06 0.15 23.87 | 0.2 0.98 0.29 50.1 0.2 29.56       | 0.1 0 0.3 45.74 0.2 25.91       |
|                    | Pb (0.30)                |                              | 0 1                            | 0.3 39.3                         | 0 1 0.3 30.17                    |
|                    | Ba (0.20)                |                              | 0.1                            | 0.98 0.2                         | 0.1 0.2 19.65                    |
|                    | Cu (0.20)                |                              | 25.8 1                         | 26.19 0.2                         | 20.19 0.2 20.01                  |

*aCacao industry function.  
*bChocolate flavor function.  
*cHuman health function.  
*dFood safety function.
### Table 3. Summary of spreadsheets of the cacao quality index of cropping site characterized by abrupt Dystrophic Red-Yellow Argisol located in humid region of Bahia, Brazil.

**Cacao Quality Index – CQI (Structure)**

| Function (Weight) | Primary Indicator (Weight) | Secondary Indicator (Weight) | Sample Observation 1 (CQI = 0.47) | Sample Observation 2 (CQI = 0.61) | Sample Observation 3 (CQI = 0.55) |
|-------------------|---------------------------|------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| CIF** (0.20)      | Lipids (0.40)             |                              | 342.12                            | 403.66                            | 180.34                            |
|                   | pH (0.25)                 |                              | 5.93                              | 5.77                              | 6.80                             |
| Total Acidity (0.25) | Total Phenols (0.10)    |                              | 15.00                            | 15.27                            | 16.08                            |
|                   | Proteins (0.10)           |                              | 68.02                            | 68.08                            | 138.22                           |
| Total Free Amino Acids (0.20) | Simple Carbohydrate (0.15) |                              | 28.12                            | 30.35                            | 1.16                             |
|                   | Purine Alkaloids (0.15)   |                              | 5.47                              | 5.05                              | 1.16                             |
|                   | Total Acidity (0.10)      |                              | 15.00                            | 15.27                            | 1.16                             |
|                   | Organic Acids (0.10)      |                              | 2.25                              | 1.42                              | 1.16                             |
|                   | Micronutrients (0.10)     |                              | 0.00                              | 0.00                              | 0.00                             |
|                   | Potentially Toxic Elements (0.10) |                       | 0.00                              | 0.00                              | 0.00                             |
|                   | Macronutrients (0.20)     |                              | 2.21                              | 2.89                              | 41.13                            |
|                   | Fe (0.40)                 |                              | 2.47                              | 2.89                              | 2.47                             |
|                   | Zn (0.40)                 |                              | 2.56                              | 2.89                              | 2.56                             |
|                   | Mn (0.20)                 |                              | 2.00                              | 2.89                              | 2.00                             |
|                   | Cu (0.20)                 |                              | 0.70                              | 2.89                              | 0.70                             |
|                   | Cd (0.30)                 |                              | 1.28                              | 2.89                              | 1.28                             |
|                   | Pb (0.30)                 |                              | 4.36                              | 2.89                              | 4.36                             |
|                   | Ba (0.20)                 |                              | 28.12                            | 2.89                              | 28.12                           |
|                   | Cu (0.20)                 |                              | 12.8                              | 2.89                              | 12.8                             |

**CIF** = Cacao industry function.
**CFF** = Chocolate flavor function.
**HFF** = Human health function.
**FSF** = Food safety function.

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**CIF**

| Function (Weight) | Primary Indicator (Weight) | Indicator | Score | Indicator % | Function % |
|-------------------|---------------------------|----------|-------|-------------|------------|
| Lipids (0.40)     |                           |          |       |             |            |
| pH (0.25)         |                           |          |       |             |            |
| Total Acidity (0.25) | Total Phenols (0.10)    |          |       |             |            |
| Proteins (0.10)   |                           |          |       |             |            |
| Total Free Amino Acids (0.20) | Simple Carbohydrate (0.15) |          |       |             |            |
| Purine Alkaloids (0.15) | Total Acidity (0.10)      |          |       |             |            |
| Organic Acids (0.10) | Micronutrients (0.10)     |          |       |             |            |
|                   | Potentially Toxic Elements (0.10) |          |       |             |            |
|                   | Macronutrients (0.20)     |          |       |             |            |
|                   | Fe (0.40)                 |          |       |             |            |
|                   | Zn (0.40)                 |          |       |             |            |
|                   | Mn (0.20)                 |          |       |             |            |
|                   | Cu (0.20)                 |          |       |             |            |
|                   | Cd (0.30)                 |          |       |             |            |
|                   | Pb (0.30)                 |          |       |             |            |
|                   | Ba (0.20)                 |          |       |             |            |
|                   | Cu (0.20)                 |          |       |             |            |

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**CFF**

| Function (Weight) | Primary Indicator (Weight) | Indicator | Score | Indicator % | Function % |
|-------------------|---------------------------|----------|-------|-------------|------------|
| Lipids (0.40)     |                           |          |       |             |            |
| pH (0.25)         |                           |          |       |             |            |
| Total Acidity (0.25) | Total Phenols (0.10)    |          |       |             |            |
| Proteins (0.10)   |                           |          |       |             |            |
| Total Free Amino Acids (0.20) | Simple Carbohydrate (0.15) |          |       |             |            |
| Purine Alkaloids (0.15) | Total Acidity (0.10)      |          |       |             |            |
| Organic Acids (0.10) | Micronutrients (0.10)     |          |       |             |            |
|                   | Potentially Toxic Elements (0.10) |          |       |             |            |
|                   | Macronutrients (0.20)     |          |       |             |            |
|                   | Fe (0.40)                 |          |       |             |            |
|                   | Zn (0.40)                 |          |       |             |            |
|                   | Mn (0.20)                 |          |       |             |            |
|                   | Cu (0.20)                 |          |       |             |            |
|                   | Cd (0.30)                 |          |       |             |            |
|                   | Pb (0.30)                 |          |       |             |            |
|                   | Ba (0.20)                 |          |       |             |            |
|                   | Cu (0.20)                 |          |       |             |            |

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**HFF**

| Function (Weight) | Primary Indicator (Weight) | Indicator | Score | Indicator % | Function % |
|-------------------|---------------------------|----------|-------|-------------|------------|
| Lipids (0.40)     |                           |          |       |             |            |
| pH (0.25)         |                           |          |       |             |            |
| Total Acidity (0.25) | Total Phenols (0.10)    |          |       |             |            |
| Proteins (0.10)   |                           |          |       |             |            |
| Total Free Amino Acids (0.20) | Simple Carbohydrate (0.15) |          |       |             |            |
| Purine Alkaloids (0.15) | Total Acidity (0.10)      |          |       |             |            |
| Organic Acids (0.10) | Micronutrients (0.10)     |          |       |             |            |
|                   | Potentially Toxic Elements (0.10) |          |       |             |            |
|                   | Macronutrients (0.20)     |          |       |             |            |
|                   | Fe (0.40)                 |          |       |             |            |
|                   | Zn (0.40)                 |          |       |             |            |
|                   | Mn (0.20)                 |          |       |             |            |
|                   | Cu (0.20)                 |          |       |             |            |
|                   | Cd (0.30)                 |          |       |             |            |
|                   | Pb (0.30)                 |          |       |             |            |
|                   | Ba (0.20)                 |          |       |             |            |
|                   | Cu (0.20)                 |          |       |             |            |

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**FSF**

| Function (Weight) | Primary Indicator (Weight) | Indicator | Score | Indicator % | Function % |
|-------------------|---------------------------|----------|-------|-------------|------------|
| Lipids (0.40)     |                           |          |       |             |            |
| pH (0.25)         |                           |          |       |             |            |
| Total Acidity (0.25) | Total Phenols (0.10)    |          |       |             |            |
| Proteins (0.10)   |                           |          |       |             |            |
| Total Free Amino Acids (0.20) | Simple Carbohydrate (0.15) |          |       |             |            |
| Purine Alkaloids (0.15) | Total Acidity (0.10)      |          |       |             |            |
| Organic Acids (0.10) | Micronutrients (0.10)     |          |       |             |            |
|                   | Potentially Toxic Elements (0.10) |          |       |             |            |
|                   | Macronutrients (0.20)     |          |       |             |            |
|                   | Fe (0.40)                 |          |       |             |            |
|                   | Zn (0.40)                 |          |       |             |            |
|                   | Mn (0.20)                 |          |       |             |            |
|                   | Cu (0.20)                 |          |       |             |            |
|                   | Cd (0.30)                 |          |       |             |            |
|                   | Pb (0.30)                 |          |       |             |            |
|                   | Ba (0.20)                 |          |       |             |            |
|                   | Cu (0.20)                 |          |       |             |            |

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*a* Cacao industry function.
*b* Chocolate flavor function.
*c* Human health function.
*d* Food safety function.
Table 4. Summary of characteristics of biochemical attributes observed in dry cacao beans.

| Attribute       | Unit                | Value or range of values | Sample Descriptions                                                                 | Literature                           |
|-----------------|---------------------|--------------------------|-------------------------------------------------------------------------------------|--------------------------------------|
| pH              | Dimensionless       | 4.5–5.5                  | For fermented process in cacao beans, most of enzymes requires this range of pH optimum. | Biehl et al. [20]                    |
| Total acidity   | mEq NaOH 100 g⁻¹    | 5.0–5.5                  | Fermented cacao beans with higher flavor potential.                                | Biehl et al. [21]                    |
|                 |                     | 4.0–4.5                  | Fermented cacao beans with low flavor potential.                                   | Biehl & Voigt [22]                   |
|                 |                     | 12–15                    | Desired range by the chocolate industry in cacao beans.                            | Lopez & Passos [23]                  |
|                 |                     | 39                       | Maximum total fixed acidity.                                                       | Bonvehí & Coll [24]                  |
|                 |                     | 35                       | A nonvolatile fixed acidity.                                                       | Bonvehí & Coll [24]                  |
|                 |                     | 8–29                     | Dry cacao beans from different geographic regions.                                 | Holm et al. [25]                     |
| Acetic acid     | mg g⁻¹              | 4.19–8.09                | Dry cacao beans from different geographic regions.                                 | Jinap & Dimick [26]                  |
|                 |                     | 1.3–11.8                 | Dry cacao beans from different cropping regions.                                   | Holm et al. [25]                     |
| Lactic acid     | mg g⁻¹              | 2.1–5.0                  | Dry cacao beans from different geographic regions.                                 | Jinap & Dimick [26]                  |
|                 |                     | 0.6–11.1                 | Dry cacao beans from different geographic regions.                                 | Holm et al. [25]                     |
| Sucrose         | mg g⁻¹              | 0.54                     | Supposed samples of dry cacao beans in ideal condition.                             | Reineccius et al. [27]               |
|                 |                     | 9.94                     | Supposed samples of dry cacao beans in not ideal condition.                        | Reineccius et al. [27]               |
|                 |                     | 0.82                     | Dry beans of Forastero cacao from São Paulo, Brazil.                               | Brito et al. [28]                    |
|                 |                     | 1.12                     | Dry beans of Common cacao (Forastero) from Bahia, Brazil.                          | Loureiro et al. [29]                 |
| Fructose        | mg g⁻¹              | 3.6                      | Supposed samples of dry cacao beans in ideal condition.                             | Reineccius et al. [27]               |
|                 |                     | 4.9                      | Supposed samples of dry cacao beans in not ideal condition.                        | Reineccius et al. [27]               |
|                 |                     | 1.27                     | Dry beans of Forastero cacao from São Paulo, Brazil.                               | Brito et al. [28]                    |
|                 |                     | 5.94                     | Dry beans of Common cacao (Forastero) from Bahia, Brazil.                          | Loureiro et al. [29]                 |
| Glucose         | mg g⁻¹              | 0.43                     | Supposed samples of dry cacao beans in ideal condition.                             | Reineccius et al. [27]               |
|                 |                     | 3.4                      | Supposed samples of dry cacao beans in not ideal condition.                        | Reineccius et al. [27]               |
|                 |                     | 1.93                     | Dry beans of Common cacao (Forastero) from Bahia, Brazil.                          | Loureiro et al. [29]                 |
| Lipids          | g kg⁻¹              | 500                      | Typical average content approximates reported in dry cacao beans.                  | Biehl et al. [30], Avila & Dias [31], Figueira et al. [32], Beckett [33,34], Cruz [35] |
| Proteins        | g kg⁻¹              | 457.5                    | Dry beans of PH-16 cacao clone.                                                     | Biehl et al. [30]                    |
|                 |                     | 150–200                  | Typical range of contents reported in dry cacao beans.                             | Biehl et al. [30]                    |
| Free Amino Acids| mg g⁻¹              | 118                      | Dry beans of Forastero cacao from São Paulo, Brazil.                               | Brito et al. [28]                    |
|                 |                     | 137.5                    | Dry beans of PH-16 cacao clone.                                                     | Cruz [35]                            |
|                 |                     | 168.6                    | Dry beans of Common cacao (Forastero) from Bahia, Brazil.                          | Loureiro et al. [29]                 |
|                 |                     | 5.0–25.2                 | Range of contents related to the cacao beans from different cropping regions.      | Rohsius et al. [37]                  |
|                 |                     | 13.0                     | Average content related to the cacao beans from different cropping regions.        | Rohsius et al. [37]                  |
|                 |                     | 35.3                     | Dry beans of Forastero cacao from São Paulo, Brazil.                               | Brito et al. [28]                    |
|                 |                     | 34.38–50.42              | Under-fermented cacao beans, PBC 140 cacao clone, Perak, Malaysia.                 | Yusep et al. [38]                    |
| Theobromine     | mg g⁻¹              | 8–21                     | Not information about the origin of cacao samples.                                 | Schwan & Fleet [39]                  |
|                 |                     | 16.63–29.38              | Dry cacao beans from Maylasian                                                     | Ramli et al. [40]                    |
| Caffeine        | mg g⁻¹              | 5.53                     | Dry cacao beans of PH-16 cacao clone.                                               | Cruz [35]                            |
|                 |                     | 0.8–2.3                  | Not information about the origin of cacao samples.                                 | Schwan & Fleet [39]                  |
|                 |                     | 2.52–4.98                | Dry cacao beans from Maylasian.                                                     | Ramli et al. [40]                    |

(Continued)
Table 4. (Continued).

| Attribute | Unit         | Value or range of values | Sample Descriptions | Literature          |
|-----------|--------------|--------------------------|---------------------|---------------------|
| (-)-catechin | mg g⁻¹ | 0.08 | Dry beans of PH-16 cacao clone. | Cruz et al. [41] |
| (-)-epicatechin | mg g⁻¹ | 3.0  | Dry beans of Common cacao (Forastero). | Loureiro [49] |
|                        |           | 2.25–3.91 | Dry cacao beans from Maylasian. | Ramlí et al. [40] |
| Total phenols | mg g⁻¹ | 6.65 | PH-16 cacao clone. | Cruz et al. [41] |
|                        |           | 3.49–5.27 | Dry cacao beans from Maylasian. | Ramlí et al. [40] |
|                        |           | 9.24 | Dry beans of Common cacao (Forastero). | Loureiro [49] |
|                        |           | 52.5 | PH-16 cacao clone. | Cruz et al. [42] |
|                        |           | 100  | Average value related that varying according to the geographical location. | Oliveira [43] |
|                        |           | 30–215.5 | Different genotypes from different geographic regions. | Loureiro et al. [11] |
|                        |           | 34.93–60.22 | Dry cacao beans from Maylasian. | Ramlí et al. [40] |
|                        |           | 157  | Dry beans of Forastero cacao from São Paulo, Brazil. | Brito et al. [28] |

Table 5. Summary of characteristics of mineral composition observed in dry cacao beans.

| Attribute | Unit         | Value or range of values | Sample Descriptions for dry cacao beans | Literature          |
|-----------|--------------|--------------------------|----------------------------------------|---------------------|
| N         | g kg⁻¹       | 20–24                    | Forastero cacao from Bahia, Brazil.     | Santana et al. [44] |
| P         | g kg⁻¹       | 33.4                     | Forastero cacao (Catongo) from Bahia, Brazil. | Malavolta et al. [45] |
|           |              | 21.62–23.91              | Highlight of productive cacao clones from Brazil. | Muniz et al. [46] |
| K         | g kg⁻¹       | 3.6–6.9                  | Forastero cacao from Bahia, Brazil.     | Santana et al. [44] |
|           |              | 2.1                      | Forastero cacao (Catongo) from Bahia, Brazil. | Malavolta et al. [45] |
|           |              | 2.95–3.91                | Highlight of productive cacao clones from Brazil. | Muniz et al. [46] |
|           |              | 1.96–6.21                | Different genotypes from different geographic regions. | Loureiro et al. [11] |
|           |              | 7.49–11.84               | Highlight of productive cacao clones from Brazil. | Malavolta et al. [45] |
|           |              | 4.52–25.58               | Different genotypes from different geographic regions. | Loureiro et al. [11] |
| Ca        | g kg⁻¹       | 1.0–2.1                  | Forastero cacao from Bahia, Brazil.     | Santana et al. [44] |
|           |              | 0.46–1.19                | Highlight of productive cacao clones from Brazil. | Muniz et al. [46] |
|           |              | 0.8–2.70                 | Different genotypes from different geographic regions. | Loureiro et al. [11] |
| Mg        | g kg⁻¹       | 2.6–6.6                  | Forastero cacao from Bahia, Brazil.     | Santana et al. [44] |
|           |              | 1.9                      | Forastero cacao (Catongo) from Bahia, Brazil. | Malavolta et al. [45] |
|           |              | 1.59–3.09                | Highlight of productive cacao clones from Brazil. | Muniz et al. [46] |
| Si        | g kg⁻¹       | 0.40–4.70                | Two different genotypes from different cropping sites of the same geographic region. | Loureiro et al. [11] |
| Fe        | mg kg⁻¹      | 20.0                     | Forastero cacao (Catongo) from Bahia, Brazil. | Malavolta et al. [45] |
|           |              | 22.85–159.10             | Highlight of productive cacao clones from Brazil. | Muniz et al. [46] |
| Mn        | mg kg⁻¹      | 28                       | Forastero cacao (Catongo) from Bahia, Brazil. | Malavolta et al. [45] |
|           |              | 7.57–92.02               | Highlight of productive cacao clones from Brazil. | Muniz et al. [46] |
|           |              | 3.98–10.36               | Highlight of productive cacao clones from Brazil. | Loureiro et al. [11] |
| Zn        | mg kg⁻¹      | 47                       | Forastero cacao (Catongo) from Bahia, Brazil. | Malavolta et al. [45] |
|           |              | 23.66–38.78              | Highlight of productive cacao clones from Brazil. | Muniz et al. [46] |
| Cu        | mg kg⁻¹      | 16                       | Forastero cacao (Catongo) from Bahia, Brazil. | Malavolta et al. [45] |
|           |              | 14.04–23.55              | Highlight of productive cacao clones from Brazil. | Muniz et al. [46] |
| Cd        | mg kg⁻¹      | 0.06–1.50                | Forastero cacao (Catongo) from Bahia, Brazil. | Malavolta et al. [45] |
| Ba        | mg kg⁻¹      | 1.90–11.70               | Highlight of productive cacao clones from Brazil. | Muniz et al. [46] |
| Pb        | mg kg⁻¹      | 0.0–4.09                 | Highlight of productive cacao clones from Brazil. | Loureiro et al. [11] |
performance of each function, and each function is individually the reflection of a certain set of attributes (Tables 2 and 3). For interpretation purposes, the CQI scores have three classifications: ‘good’, when the score is ≥0.70; ‘regular’ when values are between 0.31 and 0.69; and, ‘bad’, when the score is ≤0.30.

**Statistical analysis**

Data manipulation and statistical procedures used in this study were performed in R Program.[67]

**Results**

The baseline values and threshold limits (upper and lower) from different scoring curves (SSF types) showed in Table 7 were established according to published data about dry cacao beans (Tables 2–6) and expert opinion. Table 8 shows the scores of the CQI and its functions (CIF, CFF, HHF and FSF).

The cropping sites typic Dystrophic Red-Yellow Argisol (10 PVAd) and abrupt Dystrophic Red-Yellow Argisol (3 PVAd) correspond to the highest and lowest CQI scores obtained in this study (Table 8). The 10 PVAd reached the CQI score of 0.692, and obtained 0.1231 on CIF (0.20), 0.1847 on CFF (0.30), 0.2012 on HHF (0.30) and 0.1831 on FSF (0.20) (Table 8). In turn, the 3 PVAd reached the CQI score of 0.5417, and obtained 0.0989 on the CIF (0.20), 0.1582 on the CFF (0.30), 0.1869 on the HHF (0.30) and 0.0977 on the FSF (0.20) (Table 8). By the SiBCS these soils differ only by the typical character (10 PVAd) and abrupt (3 PVAd). These two cropping sites were also characterized by the cabruca system, differing only in shade tree density per hectare, 35 in the 10 PVAd and 60 in the 3 PVAd (Table 1).

The relative percentages to the weights (potential scores) of the CQI functions in the 10 PVAd were: 60% CIF, 60% CFF, 66% HHF, 90% FSF (Table 8). In 3 PVAd, the relative percentages were: 50% CIF, 53% CFF, 63.33% HHF, 50% FSF (Table 8). None of the cropping sites scored scores that could be “bad” or “good” (Table 8). Summaries of the CQI calculation worksheets for all three sample observations corresponding to sites 10 PVAd and 3 PVAd are shown in Tables 2 and 3, respectively. Tables 2 and 3 show the structure of the CQI and all the information necessary to obtain the final scores. The real value of each of the quality indicators obtained from the chemical analyzes is shown as the observed value because it corresponds to the observation of the sample of the respective cropping site (Tables 2 and 3).

Tables 2 and 3 also show the original scores of the indicators after the definition of standardized scoring functions and the scorching itself by the application of Equations 1 and 2 described in the methodology of this study. Then, the scores corrected by the weight of each primary indicator and the relative percentage of the contribution of each of them to the score of its respective functions (Tables 2 and 3) are also shown. Functions scores and the relative percentage of contribution in CQI are shown sequence (Tables 2 and 3).

**Discussion**

The CQI (Table 8) was able to differentiate the studied cacao agroeocysystems by the joint interpretation of attributes of cacao quality according to the needs of the cultivation in the cacao region of Bahia, Brazil and its environmental nuances that integrated the theoretical structure of this methodology. The two cropping sites selected for CQI methodological demonstration, 10 PVAd and 3 PVAd, showed the same cropping system (Cabruca) may have a low or high potential for the production of quality cacao beans. But this depends on technical interventions such as shade management, removal of old plants, and replanting and nutritional management.[68]

The upper threshold set for the lipids indicator (500 g kg\(^{-1}\)) (Table 7) is approximately 10% higher than the average content of this attribute of PH-16 cacao beans (366.5 g kg\(^{-1}\).[10] Lipids content is one of the attributes that most differentiate the cacao genotypes.[11] It is necessary to check
Table 6. Information about critical limits, recommended intakes, deficiency and toxicity of mineral elements Mn, Fe, Zn, Cu, Cd, Ba and Pb used for interpretation of the scores these cacao quality indicators.

| Variable | Critical limits for cacao beans | Recommended Intakes | Deficiency | Toxicity |
|----------|--------------------------------|---------------------|------------|----------|
| Mn       | Undefined.                     | 2 mg kg\(^{-1}\) (body weight) day\(^{-1}\) \(^{[47]}\) | Several diseases in humans and animals. \(^{[58]}\) | Is not been reported in humans, even though certain vegetarian diets could provide up to 20 mg day\(^{-1}\) of manganese. \(^{[47,49]}\) |
| Fe       | Undefined.                     | Nomative requirements from diets differing in iron bioavailability (15%, 12%, 10%, and 5%), different groups of age ranges and genres (infants and children, adults, male, female, postmenopausal and lactating) range between 3.9 to 65.4 mg kg\(^{-1}\) (body weight) day\(^{-1}\). \(^{[50]}\) | In human populations is still a challenge to global public health. \(^{[51]}\) | Ingestion of more than 20 mg kg\(^{-1}\) of iron supplements or medications can cause numerous health changes (Aggett; FNB & IOM) \(^{[52,53]}\), and values above 60 mg kg\(^{-1}\) can lead to multisystem organ failure, coma, convulsions, and even death. \(^{[54,55]}\) |
| Zn       | Undefined.                     | Nomative requirements for zinc from diets differing in zinc bioavailability (15%, 30%, 50% and 80%), range between 36 to 1200 µg kg\(^{-1}\) (body weight) day\(^{-1}\) (FAO & WHO, 2005). \(^{[50]}\) The upper level of zinc intake for an adult man is set at 45 mg day\(^{-1}\) (690 mmol day\(^{-1}\)) and extrapolated to other groups in relation to basal metabolic rate. For children this extrapolation means an upper limit of intake of 23–28 µg kg\(^{-1}\) (350–430 mmol day\(^{-1}\)), which is close to what has been used in some of the zinc supplementation studies. \(^{[50]}\) | It has been estimated that 2 billion people on the planet are zinc deficient. \(^{[56]}\) | Zinc toxicity in humans is minimal. \(^{[57]}\) However, the toxicity signs are nausea, vomiting, diarrhea, fever, and lethargy and have been observed after ingestion of 4–8 g (60–120 mmol) of zinc. \(^{[50]}\) |
| Cu       | 50 mg kg\(^{-1}\) (EU, 2013) \(^{[58]}\) | 10 mg kg\(^{-1}\) (body weight) day\(^{-1}\) \(^{[59]}\) | Clinically evident or frank dietary copper deficiency is relatively uncommon. \(^{[60]}\) | Copper toxicity is rare in the general population. \(^{[59]}\) |
| Cd       | 0.60 mg kg\(^{-1}\) (EU, 2014) \(^{[61]}\) | The Joint FAO/WHO Expert Committee on Food Additives established a provisional tolerable monthly intake of 25 µg kg\(^{-1}\) (body weight), whereas the EFSA Panel on Contaminants in the Food Chain nominated a tolerable weekly intake of 2.5 µg kg\(^{-1}\) (body weight) to ensure sufficient protection of all consumers. \(^{[62]}\) | It is not nutrient. | Cadmium toxicity leads to renal and bone problems and reproductive difficulties. \(^{[62]}\) |
| Ba       | Undefined.                     | Using a no-observed-adverse-effect level in humans of 0.21 mg barium kg\(^{-1}\) (body weight) per day, a tolerable intake value of 0.02 mg kg\(^{-1}\) (body weight) day\(^{-1}\) for barium and barium compounds has been recommended. \(^{[63]}\) | It is not nutrient. | It is not nutrient. |
| Pb       | 10 mg kg\(^{-1}\) (EU, 2006) \(^{[64]}\) | Lead is considered one of the most toxic metals and is undesirable in every type of food. \(^{[65]}\) | It is not nutrient. | The toxicity of lead has been widely reported, including the numerous symptoms of lead poisoning. \(^{[66]}\) |
whether the average content of lipids of the PH-16 clone beans is a genetic trait, or is it just an environmental effect. Therefore, some of the observations of cropping sites 10 PVAd (Table 2) and 3 PVAd (Table 3) obtained corrected scores of the lipids indicator equal to zero. The CQI was developed for universal application; however, it is necessary to characterize different genotypes in order to obtain a quality map that allows different interpretations and technical applications.

| Quality Indicator | Function | L  | B  | U  | B1 | O  | B2 | Curve Signal | Curve Slope |
|-------------------|----------|----|----|----|----|----|----|--------------|-------------|
| pH                | More is better<sup>a</sup> | 4.00 | 5.00 | 6.00 | | | | + | 2.634 |
| Total Acidity     | Optimum<sup>b</sup> | 10.00 | 17.00 | 12.00 | 13.50 | 15.00 | + and - | 1.112 |
| Acetic Acid       | Less is better<sup>c</sup> | 1.00 | 2.00 | 3.00 | | | | - | 2.781 |
| Lactic Acid       | Less is better<sup>c</sup> | 0.40 | 2.20 | 5.00 | | | | - | 0.715 |
| Sucrose           | More is better<sup>a</sup> | 1.00 | 1.50 | 2.00 | | | | + | 5.005 |
| Fructose          | More is better<sup>a</sup> | 2.00 | 5.50 | 9.00 | | | | + | 0.834 |
| Glucose           | More is better<sup>a</sup> | 0.50 | 3.00 | 5.00 | | | | + | 1.001 |
| Lipids            | More is better<sup>a</sup> | 300.00 | 400.00 | 500.00 | | | | + | 0.025 |
| Proteins          | More is better<sup>a</sup> | 120.00 | 160.00 | 200.00 | | | | + | 0.063 |
| Amino Acids       | More is better<sup>a</sup> | 5.00 | 15.00 | 25.00 | | | | + | 0.250 |
| Catechin          | More is better<sup>a</sup> | 0.50 | 2.00 | 4.00 | | | | + | 1.001 |
| Epicatechin       | More is better<sup>a</sup> | 0.50 | 2.00 | 4.00 | | | | + | 0.834 |
| Total Phenols     | Optimum<sup>b</sup> | 20.00 | 100.00 | 40.00 | 60.00 | 80.00 | + and - | 0.072 |
| Theobromine       | Less is better<sup>c</sup> | 5.00 | 20.00 | 40.00 | | | | - | 0.125 |
| Caffeine          | Less is better<sup>c</sup> | 4.00 | 6.00 | 8.00 | | | | - | 1.001 |
| Nitrogen          | More is better<sup>a</sup> | 1.50 | 2.20 | 3.00 | | | | + | 2.503 |
| Phosphorus        | More is better<sup>a</sup> | 1.50 | 2.20 | 3.00 | | | | + | 1.854 |
| Potassium         | More is better<sup>a</sup> | 4.00 | 6.00 | 8.00 | | | | + | 1.001 |
| Calcium           | More is better<sup>a</sup> | 1.50 | 2.30 | 3.00 | | | | + | 2.634 |
| Magnesium         | More is better<sup>a</sup> | 1.00 | 2.00 | 3.00 | | | | + | 1.221 |
| Silicon           | More is better<sup>a</sup> | 0.50 | 1.50 | 3.00 | | | | + | 1.788 |
| Iron              | More is better<sup>a</sup> | 10.00 | 20.00 | 30.00 | | | | + | 0.167 |
| Zinc              | More is better<sup>a</sup> | 15.00 | 30.00 | 50.00 | | | | + | 0.125 |
| Copper            | Optimum<sup>b</sup> | 5.00 | 50.00 | 15.00 | 28.00 | 40.00 | + and - | 0.173 |
| Manganese         | More is better<sup>a</sup> | 10.00 | 25.00 | 40.00 | | | | + | 0.14 |
| Barium            | Less is better<sup>c</sup> | 1.00 | 5.00 | 8.00 | | | | - | 0.371 |
| Cadmium           | Less is better<sup>c</sup> | 0.10 | 0.35 | 0.60 | | | | - | 7.150 |
| Lead              | Less is better<sup>c</sup> | 0.00 | 0.50 | 1.00 | | | | - | 2.503 |

<sup>a</sup>More is better: L – lower threshold, at which or below the score is 0, B – baseline, at which score is 0.5, U – upper threshold, at which or above score is 1.0

<sup>b</sup>Optimum: B1 – lower baseline is 0.5, O – Optimum level, at which score is 1.0, B2 – upper baseline is 0.5.

<sup>c</sup>Less is better: L – lower threshold, at which or below the score is 1.0, B – baseline, at which score is 0.5, and U – upper threshold, at which or above score is 0.

Whether the average content of lipids of the PH-16 clone beans is a genetic trait, or is it just an environmental effect. Therefore, some of the observations of cropping sites 10 PVAd (Table 2) and 3 PVAd (Table 3) obtained corrected scores of the lipids indicator equal to zero. The CQI was developed for universal application; however, it is necessary to characterize different genotypes in order to obtain a quality map that allows different interpretations and technical applications.
Table 8. Summary of scores of the cacao quality index and its functions (cacao in 12 cropping sites characterized by soil types cultivated with PH-16 cacao clone in the humid region of Bahia, Brazil.

| Rank | Cropping sites | Cacao Quality Index (1.0) | Classification | Cacao Industry (0.20) | Chocolate Flavor (0.30) | Human Health (0.30) | Food Safety (0.20) | Average ± Standard Deviation (n = 3) |
|------|----------------|--------------------------|----------------|----------------------|------------------------|----------------------|-------------------|-------------------------------------|
| 1    | 10 PVAd        | 0.692 ± 0.067            | Regularb       | 0.1231 ± 0.0072      | 0.1847 ± 0.042         | 0.2012 ± 0.0036      | 0.1831 ± 0.0264    |                                     |
| 2    | 1 LAd cam      | 0.6579 ± 0.0061          |                | 0.1073 ± 0.02        | 0.1695 ± 0.0147        | 0.1687 ± 0.014      | 0.1944 ± 0.0069    |                                     |
| 3    | 4 LAd          | 0.6372 ± 0.0379          |                | 0.1361 ± 0.0427      | 0.1667 ± 0.0191        | 0.1732 ± 0.0059      | 0.1611 ± 0.0314    |                                     |
| 4    | 7 CXd          | 0.6283 ± 0.0959          |                | 0.1305 ± 0.0636      | 0.1934 ± 0.0374        | 0.1895 ± 0.02       | 0.1148 ± 0.0249    |                                     |
| 5    | 12 PVAd coe    | 0.5878 ± 0.0264          |                | 0.1154 ± 0.0119      | 0.1435 ± 0.0127        | 0.2026 ± 0.0184      | 0.1264 ± 0.016     |                                     |
| 6    | 11 PVA ali     | 0.5871 ± 0.0716          |                | 0.1079 ± 0.0196      | 0.1785 ± 0.0386        | 0.1799 ± 0.0104      | 0.1207 ± 0.0159    |                                     |
| 7    | 9 PAd lat      | 0.5633 ± 0.0269          |                | 0.1043 ± 0.015       | 0.1291 ± 0.0069        | 0.1902 ± 0.0142      | 0.1397 ± 0.0095    |                                     |
| 8    | 5 LVAd         | 0.5605 ± 0.0361          |                | 0.1012 ± 0.0259      | 0.148 ± 0.033          | 0.1579 ± 0.0132      | 0.1535 ± 0.0272    |                                     |
| 9    | 2 PVAd         | 0.5533 ± 0.0309          |                | 0.0922 ± 0.0229      | 0.1414 ± 0.0296        | 0.2004 ± 0.0154      | 0.1193 ± 0.0301    |                                     |
| 10   | 6 PVAe cam     | 0.5513 ± 0.0363          |                | 0.0801 ± 0.0238      | 0.145 ± 0.0359         | 0.1887 ± 0.0183      | 0.1376 ± 0.0257    |                                     |
| 11   | 8 LVAd arg     | 0.5428 ± 0.0241          |                | 0.0711 ± 0.0027      | 0.1658 ± 0.0328        | 0.2024 ± 0.0184      | 0.1035 ± 0.0022    |                                     |
| 12   | 3 PVAd         | 0.5417 ± 0.0689          |                | 0.0989 ± 0.0287      | 0.1582 ± 0.0455        | 0.1869 ± 0.0133      | 0.0977 ± 0.003     |                                     |

*a* Cropping sites characterized as soil types by Brazilian System of Soil Classification [13]: cambisolic Dystrophic Yellow Latosol (1 LAd cam); typic Dystrophic Red-Yellow Argisol (2 PVAd); abrupt Dystrophic Red-Yellow Argisol (3 PVAd); typic Dystrophic Yellow Latosol (4 LAd); typic Dystrophic Red-Yellow Latosol (5 LVAd); cambisolic Eutrophic Red-Yellow Argisol (6 PVAe cam); typic Dystrophic Haplic Cambisol (7 CXd); argisolic Dystrophic Red-Yellow Latosol (8 LVAd arg); latosolic Dystrophic Yellow Argisol (9 PAd lat); typic Dystrophic Red-Yellow Argisol (10 PVAd); typic Alitic Red-Yellow Argisol (11 PVA ali); abrupt Cohesive Dystrophic Red-Yellow Argisol (12 PVAd coe).

*b* When the values are between 0.31 and 0.69.
In Table 3 that characterizes the cropping site with lower performance of the CQI, 3 PVAd, it is possible to verify that the main primary indicators that would interfere with the differences found in relation to the site 10 PVAd (Table 2) were proteins, total free amino acids, simple carbohydrates, total acidity, cadmium and barium. The FSF sample observations for cropping site 3 PVAd (Table 3) reached approximately 50% of the weight of this function. In contrast, the cropping site 10 PVAd (Table 2) reached approximately 100% of the FSF weight. For both cropping sites 3 PVAd and 10 PVAd high levels of potentially toxic elements (PTE). The FSF was specially created to detect unsatisfactory levels of PTE, Cd, Pb, Ba and Cu in cacao beans (Tables 2 and 3). There is growing worldwide concern about the levels of these PTEs in food, so there are some international regulations that define the permissible limits of these elements. The discriminant power of the FSF reveals the importance of the method proposed by the CQI for complete studies on the quality of cacao beans and also the usefulness of this index to monitor and differentiate the cacao produced in different cropping systems. This methodology can be applied and/or adapted in regional studies because the critical limits of the CQI indicators for cacao agroecosystems (Tables 4 and 6) were based on the cropping, technological and environmental reality of the cacao processing.

Conclusion

The typic Dystrophic Red-Yellow Argisol, in the cabruca cropping system with 35 shade trees per hectare, reached the highest CQI score. The lowest score obtained from the CQI corresponded to the site characterized by the abrupt Dystrophic Red-Yellow Argisol, in the cabruca cropping system with 60 shade trees per hectare. All cropping sites obtained CQI values between 0.54 and 0.69 and were therefore classified as a regular index according the range values of 0.39 to 0.69 established as criteria of this classification. The primary indicators that determined the differences between the highest and lowest CQI score, corresponding to the two Dystrophics Red-Yellow Argisols, were proteins, total free amino acids, simple carbohydrates (sucrose, fructose and glucose), total acidity, cadmium and barium.

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