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Flavor Characteristics of Three Indonesian Cocoa Clones in Four Environments

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Abstract: The non-aromatic genotypes are known to possess the capacity to produce aromatic cocoa beans when planted in strategic environments with specified soil compositions. Therefore, this study aimed to identify genetic responses to the flavor of cocoa beans in different growing environments. A total of three superior cocoa clones, namely the aromatic (MCC 02) and non-aromatic genotypes (Sulawesi 1 and Sulawesi 2), were used. A completely randomized block design was utilized with three replications at four locations with different agro-climatic types, including Jember in East Java (dry area, low land), Pringsewu (dry area, low land), Pesawaran (wet area, medium land) in Lampung, and Soppeng in South Sulawesi (dry area, medium land), which served as the control location of FFC producers. Additionally, the sensory properties were assessed by three trained and certified panelists. The results showed that both genetic and environmental factors significantly influenced the flavor characteristics of Indonesian cocoa beans. Non-aromatic genotypes cultivated in Pesawaran and Soppeng demonstrated the ability to produce aromatic beans. Significant differences were observed in the volatile characteristics of aromatic and non-aromatic genotypes. Compounds such as alkaloids, pyrazine, and alcohol dominated cocoa beans produced in the aromatic group, while non-aromatic genotypes were dominated by terpenoids. Variations in elements and soil conditions contributed to the changes in the sensory characteristics of cocoa beans, ultimately leading to aromatic characteristics.

Keywords: aromatic; taste; genetics; environment; volatile; *Theobroma cacao* L.

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1. Introduction

Cocoa is an essential commodity that serves as the primary raw material in the chocolate industry. The demand for cocoa beans has continued to increase, particularly for those with unique sensory characteristics [1,2]. Among the sensory attributes, flavor quality is the most important parameter [3,4]. It provides added value in terms of high competitiveness in domestic and international markets, as well as obtaining a premium price above London and New York cocoa prices [1]. Numerous factors can affect the flavor, including genetics, processing methods, geographical locations, and cultivation techniques [1,5].

Indonesia is the sixth largest cocoa producer in the world, with a total production of 200,000 tons (4.26%) in 2019, of which 1% accounts for specialty cocoa [6,7]. However, since 2020, the country has seized the opportunity to supply up to 10% of the total national production of FFC (Fine Flavor Cocoa) beans [6]. FFC is a product with a balanced taste and a unique flavor derived from both white (fine) and purple bean (bulk) cocoa. It is characterized by the presence of fruity (fresh and browned fruit), floral, herbal, and woody aromas, as well as a balanced taste [6,8,9]. This specialty cocoa bean product can be produced from the Criollo and Trinitario varieties [3]. Furthermore, FFC characteristics are influenced by several factors, including the type of bean variety, genetic origin, morphological, flavor, and chemical characteristics, volatile compounds, bean and nib color, degree of fermentation,

drying, and acidity, without off-flavor [6]. Indonesia not only produces Java FFC, which is distinguished by the color of its fresh white beans [7] but also the bulk cocoa type, from Jembrana (Bali), West Sumba (East Nusa Tenggara), Payakumbuh (West Sumatra), and Soppeng (South Sulawesi).

In a previous study by Anita-Sari et al. [10], differences in flavor characteristics were observed in Indonesian cocoa genotypes from Jember with specific agroclimatic lowland and dry areas, namely aromatic and non-aromatic. Fibrianto et al. [11] reported that environmental factors such as soil, altitude, and climate affected the attributes of cocoa beans, but the study did not consider flavor characteristics. Moreover, Munoz et al. [9] stated that FFCs are produced from cocoa beans with unique characteristics, including genetics, origin, or other specific flavors. Cocoa beans from several areas in Indonesia reportedly have specific flavors based on cocoa of excellent competition; for example, those from Sumba Nusa Tenggara Timur (dry area) exhibited strong taste, medium bitterness, and astringency, as well as a floral and browned fruit aroma. Meanwhile, cocoa beans from Lima Puluh Kota West Sumatra (wet area) showed strong taste, light bitterness, and astringency with a browned and fresh fruit aroma [10,12]. These results underscore the diversity in cocoa development based on soil fertility levels and diverse agro-climatic conditions.

This genetic and environmental diversity in Indonesia provides opportunities to explore genotype suitability for specific agroclimatic conditions such as altitude, rainfall, and soil composition to produce FFC products. Therefore, this study aimed to identify the genetic response to the flavor of cocoa beans in different growing environments.

2. Materials and Methods

2.1. Study Area

This study was conducted in four different agro-climatic environments, namely: (1) Kaliwining Experimental Station, Indonesian Coffee and Cocoa Research Institute in Jember, East Java; (2) Pringsewu Sub-district, Pringsewu Regency, Lampung; (3) Padang Cermin Sub-district, Pesawaran Regency, Lampung; and (4) Liliriau Sub-district, Soppeng Regency, South Sulawesi. The agro-climatic conditions of the four test locations are shown in Table 1.

Table 1. Altitude and climate data for the four testing locations.

Location	Agroclimatic Type	Rainfall during Pod Production (mm/Year)
Jember	Low land with an altitude of 45 masl, an average rainfall of 2400–2500 mm/year, and an average temperature of 24–30 °C	2284.00
Pesawaran	Medium land with an altitude of 271.5 masl, an average rainfall of 1600–3000 mm/year, and an average temperature of 24–27 °C	2922.90
Pringsewu	Low land with an altitude of 30 masl, an average rainfall of 2000–2500 mm/year, and an average temperature of 23–31 °C	2461.00
Soppeng	Low land with an altitude of 30 masl, an average rainfall of 2000–2500 mm/year, and an average temperature of 23–31 °C	1969.00

Note: masl: m above sea level.

2.2. Genetic Materials

The aromatic (MCC 02) and non-aromatic (Sulawesi 1 and 2) clones of the genetic materials exhibited different flavor characteristics [10]. These three clones were superior in bean production and had been released by the Minister of Agriculture of Indonesia. The control beans were one of the winners in the Soppeng Regency, South Sulawesi Cocoa of Excellent competition. These control beans represented a blend of samples sourced from mixed (bulk) clones of Sulawesi 1 and 2, as well as MCC 02. The tested beans were produced separately in each of the four testing locations.

2.3. Procedures

2.3.1. Good Agriculture Practices

The cultivation of cocoa trees referred to the ICCRI procedure, which included fertilizer application, pruning, pest-disease management, and post-harvest processing. The fertilizer used was NPK 16:16:16 at 500 g per tree, while monthly pruning was performed to maintain branch structure. Pest and disease control measures were carried out monthly, and only mature legumes were harvested.

2.3.2. Fermentation Process, Pasta Making, and Cocoa Taste Test

The fermented beans from each genotype were obtained from 100 to 150 pods in one harvest. The beans were fermented on a medium scale according to the standards developed by the Indonesian Coffee and Cocoa Research Institute. The fermentation process used a box with a dimension of 70 × 70 × 50 cm for 96 h and reversed at the 48th hour. After 96 h, the beans were moved and spread on two layers of tarpaulin. Drying was subsequently carried out in a drying house with a maximum water content of 7%. The sample used for the taste test was in the form of a paste, produced by manually peeling 500 g of cocoa beans to separate the cotyledons from the shells. The beans were roasted at 120 °C for 12 min before being crushed and mashed with a paste tool for 15 min, and then the resulting paste was packed and stored at 5 °C.

The sensory analysis was carried out by three trained panelists, and samples were served one by one at 40–60 °C without sugar. To neutralize their senses and prevent bias, panelists were given drinking water and plain biscuits in between samples. The analysis was performed using a standardized flavor test developed by the Indonesian Coffee and Cocoa Research Institute and Guittard Chocolate. The attributes measured were cocoa, acidity, bitterness, astringency, fresh and browned fruit, floral, woody, spicy, nutty, and brown/roast, on a scale of 1–10, with higher values indicating a stronger attribute.

2.3.3. Volatile Compound Analysis

Volatile compound analysis referred to a previous study conducted by Anita-Sari et al. [13], and bean extraction used Wang's method [14]. Cocoa beans were ground until smooth using a mortar with liquid nitrogen. The samples were dissolved in 750 µL of extraction solution consisting of methanol, water, and formic acid in a ratio of 70:28:2 in a 1.5 mL microtube and then vortexed until well mixed. The homogeneous mixture was incubated for 30 min on ice, vortexed every 6 min, and centrifuged for 10 min at a speed of 14,000 rpm. The supernatant was separated into a new microtube, and the extraction procedure was repeated. GC-MS-QP2010 Plus Shimadzu analysis was performed to determine volatile metabolites, while the dry methanol phase was redissolved in 500 µL of 100% methanol solution, sonicated for 10 min using Branson ultrasonic 1520E-MT, homogenized, and centrifuged at 14,000 rpm for 1 min. The supernatant was collected for use in the GC-MS analysis, and the ready-to-inject solution was stored in a refrigerator at 4 °C. Furthermore, the column used was an Agilent HP-5MS with 30 m length, 0.25 mm diameter, and 0.25 m film. A total of 1 L of sample was injected using a 25:1 (v/v) split mode with a temperature of 230 °C, and the carrier gas rate (He) used was 1.12 mL/min with a linear speed of 39 cm/s. The column temperature was set at 80 °C for 2 min, increased to 15 to 310 °C/min, and held for 6 min. The transfer line and ion source temperatures were 250 and 200 °C, while the electron ionization (EI) was conducted at 0.94 kV. Additionally, spectra were recorded at 10,000 u/s and a mass range of 85−500 m/z.

2.3.4. Soil Analysis

The soil nutrient content was analyzed at the Testing Laboratory of the Indonesian Coffee and Cocoa Research Institute. The parameters analyzed included soil texture (sand, silt, and clay) and nutrient content, namely carbon (C), C/N, sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), copper (Cu), and zinc (Zn), as well as CEC and pH. Analysis of C and C/N nutrients was carried out using 100 g of the dry sample at 105 °C. C

content was assessed using a spectrophotometer based on a method by Walkey and Black, while N analysis used the distillation method following the Kjeldahl procedure [15]. Na, K+, Ca, and Mg were measured with a 1 M NH4OAc extractor at a pH of 7, while Cu and Zn were analyzed using 0.1 HCl. Furthermore, CEC analysis used 1 M NH4OAc extract, and pH was determined with an extraction method using H2O and KCl.

2.4. Data Analysis

The flavor quality profile was analyzed using a spider chart created with the Microsoft Excel 2019 program. Spearman correlation was used to examine the relationship between variables. The relationship between genotype and flavor characteristics was analyzed using biplot principal component analysis (PCA), and flavor-based genotype clustering was performed with dendrogram analysis. In general, the software used included STAR 2.0.1 from IRRI for the analysis of variance, Microsoft Excel 2019 and R Studio for correlation analysis, PCA biplot, and dendrogram.

3. Results

3.1. Sensory Profile

The results showed differences in the sensory characteristics of the three cocoa genotypes across different growing environments (Figure 1). The beans of Sulawesi 1 in Jember and Pringsewu did not show any aromatic flavor characteristics. However, those from Pesawaran exhibited aromatic flavor characteristics and were similar to samples from Soppeng, classified as an FFC product. Figure 1 also illustrated that MCC 02 beans from Jember and Pesawaran had aromatic flavor characteristics similar to those from Soppeng. Sulawesi 1 and MCC 02 clones grown under wet environmental conditions, such as in Pesawaran, had sensory characteristics similar to samples from Soppeng cultivated under dry, strictly defined environmental conditions. Meanwhile, Sulawesi 1 beans grown in environmental conditions similar to those in Pringsewu and Jember did not show any aromatic character.

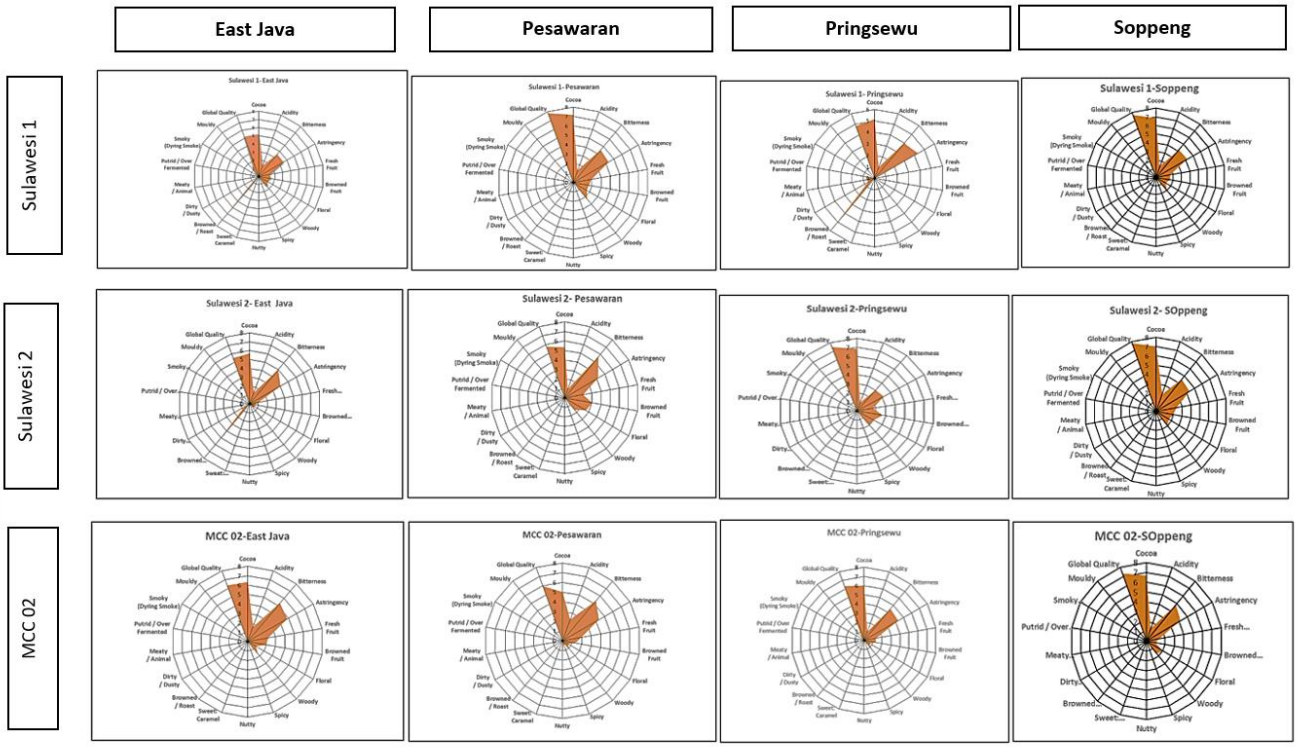
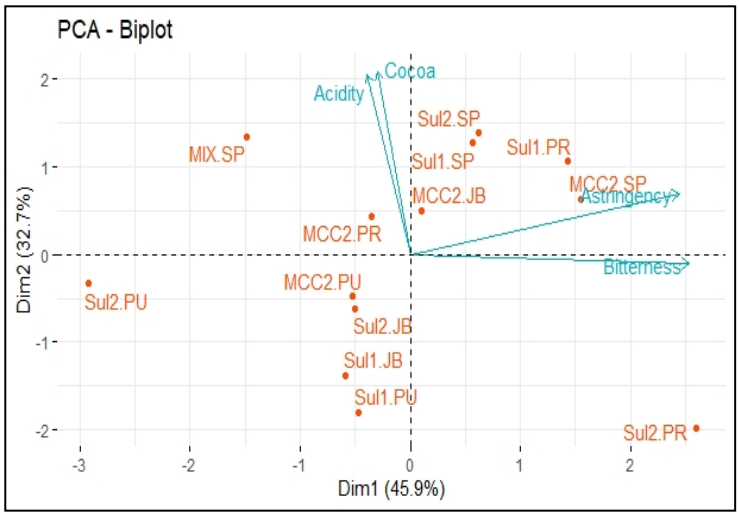


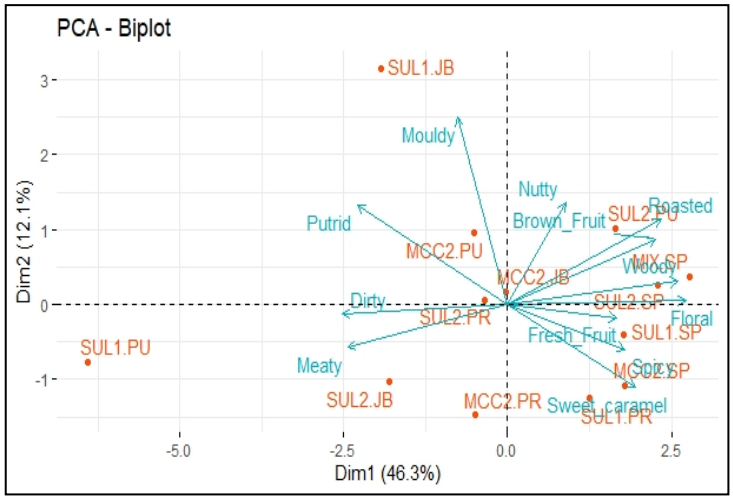
Figure 1. Sensory profiles of aromatic and non-aromatic cocoa genotypes at four different environmental conditions.

3.2. Genetic-Environmental Grouping Based on Flavor Characteristics

Figure 2a shows that certain genotypes and environmental groups have identical taste characteristics to FFC products, such as cocoa beans from Soppeng. The taste of MCC 02 beans from Jember was similar to Sulawesi 1 and Sulawesi 2 beans from Soppeng (FFC). Moreover, the taste of Sulawesi 1 beans from Pesawaran was close to that of MCC 02 from Soppeng.



(**a**)



(**b**)

Figure 2. PCA Biplot showing the (**a**) taste and (**b**) aroma of three cocoa genotypes in four different growing environments. Sul1—Sulawesi 1; Sul2—Sulawesi 2; MCC 02—location; JB—Jember; PR—Pesawaran; PU—Pringsewu; Dim1—dimention 1; Dim2—dimention 2.

Figure 2b shows that MCC 02 beans from Jember, Sulawesi 2 from Pringsewu, Sulawesi 1, and MCC 02 from Pesawaran have an aroma (odor) similar to samples from Soppeng. The aroma observed was nutty, browned fruit, roasted, woody, floral, fresh fruit, sweet, and caramel, which was included in the FFC category according to ICCO [6].

Based on taste and aroma, three genotypes and environmental groups with distinct flavor characteristics were observed. Sulawesi 1 and Sulawesi 2 beans from Pesawaran and Jember had similar taste characteristics to the bulk beans from Soppeng. MCC 02 beans from Pringsewu and Jember showed taste characteristics similar to Sulawesi 1 and Sualwesi

2, as well as MCC 02 beans from Soppeng. Meanwhile, Sulawesi 2 beans from Pringsewu had a different taste from the others, as shown in Figure 3a.

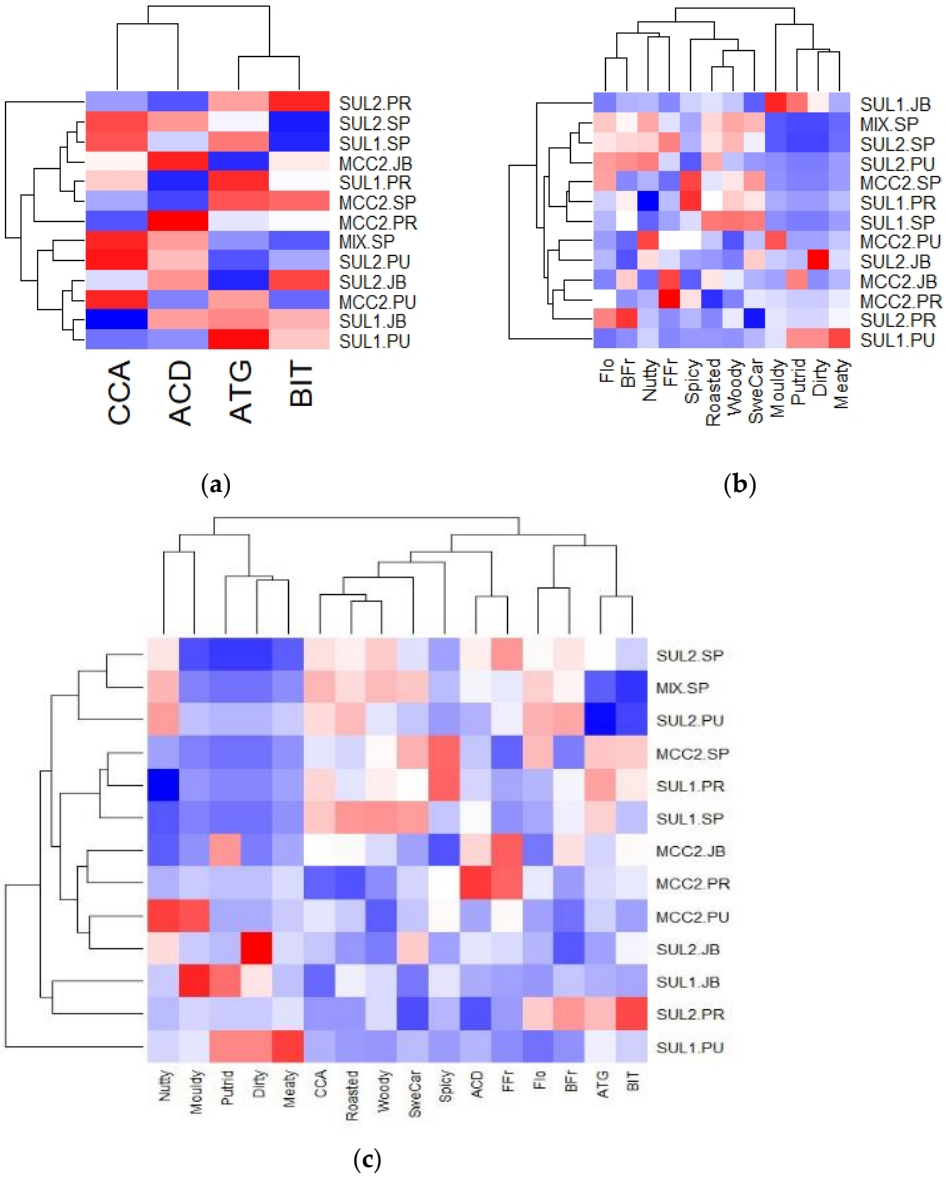


Figure 3. Clustering analysis of three cocoa genotypes in four different growing environments based on components of (**a**) taste, (**b**) aroma, as well as (**c**) taste and aroma. Sul1SP—Sulawesi 1 Soppeng; Sul1JB—Sulawesi 1 Jember; Sul1 PR—Sulawesi 1 from Pesawaran; Sul 1 PU—Sulawesi 1 from Pringsewu; Sul2 SP—Sulawesi 2 Soppeng; Sul2 JB—Sulawesi 2 Jember; Sul2 PR—Sulawesi 2 from Pesawaran; Sul 2 PU—Sulawesi 2 from Pringsewu; MCC 02 SP—MCC 02 Soppeng; MCC 02 JB—MCC 02 Jember; MCC 02 PR—MCC 02 from Pesawaran; MCC 02 PU—MCC 02 from Pringsewu; CCA—cocoa; ACD—acidity; ATG—astringency; BIT—bitter; Flo—floral; FFr—fresh fruit.

A total of three genetic and environmental groups were also observed based on aroma. Sulawesi 1 beans from Jember and Pringsewu had an aroma different from other samples. Meanwhile, the Sulawesi 2 and MCC 02 beans from Pesawaran, Jember, and Pringsewu, as well as the Sulawesi 1 beans from Pringsewu, had similar aroma characteristics with bulk beans, Sulawesi 1 and Sulawesi 2, alongside MCC 02 from Soppeng (Figure 3b).

The analysis results showed four groups of sensory characteristics from three genotypes in four growing locations. Sulawesi 2 beans from Pringsewu had similar characteristics to those from Soppeng. Figure 3c illustrates that Sulawesi 1 beans from Pesawaran,

MCC 02 from Jember, Pringsewu, Pesawaran, and Sulawesi 2 from Jember had taste and aroma characteristics similar to those of Sulawesi 1 and MCC 02 from Soppeng. Meanwhile, Sulawesi 1 beans from Jember, which had non-aromatic characteristics, were in the same group as Sulawesi 2 beans from Pesawaran. Sulawesi 1 beans from Pringsewu exhibited different characteristics compared to others.

3.3. Volatile Profile

The results showed that three cocoa genotypes (Sulawesi 1 and Sulawesi 2 as well as MCC 02) had different intensities and compositions of volatile compounds in four different environments (Table 2). This implied that each genotype had a different response to different environmental conditions.

Table 2. Volatile compounds of three cocoa genotypes from four different locations.

Compound		Area Percentage (%)											
		Sulawesi 1				Sulawesi 2				MCC 02			
		JMB	PSW	PRW	SOP	JMB	PSW	PRW	SOP	JMB	PSW	PRW	SOP
Alkohol													
3-Methyl-2-butanol	$C_5H_{12}O$	-	-	-	-	-	0.85	-	-	-	-	-	-
Hexanol	$C_{17}H_{32}O$	0.13	4.07	-	-	-	-	-	3.88	-	-	0.04	0.80
1,10-Decanediol	$C_{10}H_{22}O_2$	-	4.53	-	-	-	-	-	-	-	-	-	-
1,3 Butanediol	$C_4H_{10}O_2$	-	-	-	-	0.38	-	0.49	-	2.77	-	-	1.42
2,3 Butanediol	$C_4H_{10}O_2$	-	-	-	-	-	0.87	-	-	-	5.02	0.79	-
2-Pentanol	$C_5H_{12}O$	-	1.41	-	-	-	-	-	0.80	-	-	-	3.41
Cyclohexanol	$C_9H_{14}O_2$	-	-	-	-	-	-	0.57	-	-	-	-	-
Ethanol	$C_6H_{14}O_3$	1.13	1.35	5.42	-	2.09	-	0.99	-	1.93	0.39	0.40	-
Tridecanol	$C_{13}H_{28}O$	-	-	-	0.21	-	-	-	-	-	-	-	-
Acid													
1,2-Benzenedicarboxylic acid	$C_{16}H_{22}O_4$	0.04	-	-	-	-	-	-	-	-	-	-	-
2-Propenoic acids	$C_{10}H_{14}O_4$	-	-	0.95	-	0.43	-	-	-	-	-	0.09	-
Acetic Acids	$C_2H_4O_2$	47.31	24.87	33.08	2.81	50.17	50.08	32.50	10.22	45.89	22.14	70.09	36.35
9 Decenoic acid	$C_{10}H_{18}O_2$	-	2.29	-	0.99	-	-	-	0.73	0.07	-	-	1.01
9-Octadecenoic acid	$C_{18}H_{34}O_2$	-	3.29	4.97	-	4.53	-	7.13	-	0.66	2.04	0.33	16.79
Benzoic acid	$C_{12}H_{16}O_2$	-	-	0.31	-	-	-	-	-	-	-	-	-
Butanoic acid	$C_5H_{10}O_2$	-	-	15.32	-	6.62	1.38	12.36	-	0.18	3.51	-	-
Propanoic Acid	$C_5H_{10}O_3$	7.41	-	5.75	-	2.26	-	5.62	-	10.86	1.38	2.23	1.17
Nonanoic acid	$C_9H_{18}O_2$	-	0.85	-	-	-	-	-	-	-	-	-	-
Octanoic acid	$C_8H_{16}O_2$	-	9.13	-	1.09	-	-	-	2.92	-	-	-	3.62
Hexanedioic acid	$C_6H_{10}O_4$	-	-	0.67	-	-	-	-	-	-	-	-	-
Formic acid	$C_4H_8O_2$	-	-	-	-	-	0.63	-	-	-	-	-	-
2-Pyridinepropanoic acid	$C_{11}H_{13}NO_3$	-	-	-	-	26.59	0.36	-	-	-	-	-	-
Cyclohexanepropanoic acid	$C_9H_{16}O_2$	-	-	-	0.35	-	-	-	-	-	-	-	-
Iso-Valeric acid	$C_5H_{10}O_2$	-	-	-	-	-	-	-	-	14.85	-	10.88	-
Heptadecanoic acid	$C_{19}H_{38}O_2$	-	-	-	-	0.35	-	-	-	-	-	-	-
Ester													
Propyl ester	$C_6H_{12}O_3$	-	-	-	-	-	-	-	-	-	3.29	-	-
Ethyl ester	$C_{22}H_{44}O_2$	-	-	0.27	-	-	-	-	-	-	-	-	-
Hexadecyl ester	$C_{24}H_{48}O_2$	-	-	-	16.61	-	-	-	-	-	-	-	-
Undecanoic acid, ethyl ester	$C_{13}H_{26}O_2$	-	-	-	-	-	-	-	-	-	-	-	-
Aldehyde													
Benzaldehyde	C_7H_6O	-	-	-	-	-	-	-	-	0.14	-	0.05	-
Cyclohexaneacetaldehyde	$C_8H_{14}O$	0.06	-	-	-	-	-	-	-	-	-	-	-
Valeraldehyde	$C_8H_{14}O$	-	-	0.34	-	-	-	-	-	-	-	-	-
Alkaloid													
Caffeine	$C_8H_{10}N_4O_2$	-	-	0.75	3.51	-	-	4.77	-	2.16	-	-	-
Terpenoid													
Linalool	$C_{10}H_{20}O$	-	-	-	-	-	-	-	-	-	-	0.13	-
Pyrazine													
Pyrazine	$C_8H_{12}N_2$	0.19	-	-	-	-	-	-	-	0.28	0.19	-	-

Table 2. *Cont.*

Compound		Area Percentage (%)											
		Sulawesi 1				Sulawesi 2				MCC 02			
		JMB	PSW	PRW	SOP	JMB	PSW	PRW	SOP	JMB	PSW	PRW	SOP
Furan, Furanone													
Furan	$C_5H_{10}O_3$	-	-	-	-	-	0.05	-	-	-	-	-	-
2,5-Furandione	$C_5H_4O_3$	-	-	-	-	0.43	-	-	-	-	-	-	-
2-Butanone	$C_4H_8O_2$	-	0.43	-	-	-	-	-	-	-	-	-	-

Note: JMB—Jember; PSW—Pesawaran; PRW—Pringsewu; SOP—Soppeng.

Sulawesi 1 beans from Pesawaran (wet and medium area) showed an aromatic flavor characterized by a higher intensity and greater number of alcohol compounds compared to Sualwesi 1 from Jember and Pringsewu. In addition, furan compounds were also found compared to samples from Jember, Pringsewu, and Soppeng. Sulawesi 1 from Soppeng, which was also aromatic, had a lower intensity and variance of alcohol compounds than the other locations. The specific type of alcohol identified was tridecanol, a distinctive characteristic not found in other beans. Samples from Soppeng were also characterized by their low acid content and higher intensity of ester and terpenoid compounds. The ester content in cocoa beans influenced the formation of fruity, floral, and honey aromas [16].

Sulawesi 2 beans from Pesawaran, classified as aromatic, were characterized by a low alcohol content and the presence of furan compounds. Samples from Soppeng had high alcohol intensity and low acid content compared to the other beans. Meanwhile, Sulawesi 2 beans from Pringsewu were characterized by the presence of alkaloid compounds. MCC 02 from Pringsewu, which could not be classified in the aromatic category, had significantly higher levels of acetic acid compared to others.

Non-aromatic genotype groups were dominated by terpenoid and aldehyde content. Differences were observed in the dominance of volatile compounds in aromatic beans. Sulawesi 1, classified as aromatic, was dominated by the presence of furan, furanone, and ester compounds (Figure 4).

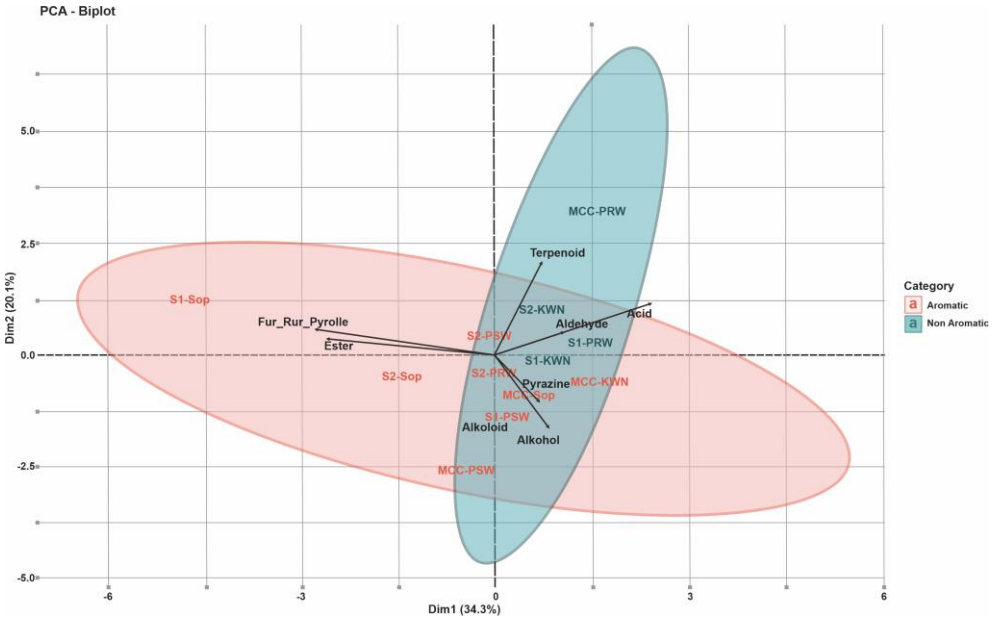


Figure 4. PCA biplot of volatile compounds of three cocoa genotypes in four different locations. Dim1—dimention 1; Dim2—dimention 2; S1—Sualwesi 01; S2—Sulawesi 02; MCC—MCC 02; Sop—Soppeng; PRW—Pringsewu; PSW—Pesawaran; KWN—Jember; Fur—Furan; Rur—Furanone.

In contrast to other aromatic beans, MCC 02 from Jember, Soppeng, and Pesawaran was more dominated by alkaloid, alcohol, and pyrazine compounds.

3.4. Agroclimatic and Soil Conditions for Cocoa Bean Aroma

Table 3 presents empirical evidence indicating that the presence of dust in the soil has a substantial impact on the overfermented characteristics of cocoa beans. Specifically, the dust content in the soil led to a significant decrease in the floral and woody aromas.

Table 3. Correlation of agroclimatic parameters and soil nutrients with cocoa bean aroma.

Component	F.Fruit	B.Fruit	Floral	Woody	Spicy	Nutty	Roast	Dirty	Meaty	O.Ferm
Sand	0.24	0.20	0.36	0.40	0.30	0.14	−0.03	−0.62	−0.02	−0.17
Dust	−0.50	−0.37	−0.78 *	−0.63	0.06	−0.39	−0.14	0.57	0.62	0.81 **
Clay	0.50	0.37	0.78 *	0.60	−0.13	0.40	0.17	−0.49	−0.67 *	−0.85 **
Carbon	0.32	−0.20	0.07	0.39	0.11	−0.36	0.22	−0.31	−0.49	−0.58
CNRatio	0.49	0.00	0.47	0.42	0.00	0.12	0.15	−0.36	−0.71	−0.78 *
Sodium	0.14	0.61	0.40	0.15	0.21	0.76 *	0.19	−0.26	−0.10	−0.18
Potassium	−0.19	−0.23	−0.56	−0.31	−0.29	−0.39	0.19	0.51	0.18	0.45
Calcium	0.22	−0.25	0.22	0.31	−0.28	−0.05	0.27	−0.12	−0.38	−0.41
KEC	0.35	−0.10	0.25	0.55	−0.34	−0.21	0.46	−0.31	−0.47	−0.43
Cuprum	0.24	−0.25	0.04	0.31	−0.36	−0.56	0.16	−0.15	−0.40	−0.19
Zink	−0.13	−0.33	−0.36	−0.40	−0.13	−0.34	−0.14	0.53	−0.18	0.00
pH	−0.14	−0.49	−0.14	0.11	−0.49	−0.51	0.13	0.15	−0.01	0.03
Rainfall	0.07	0.60	−0.14	−0.43	0.73 *	0.12	−0.73 *	0.12	0.12	0.12
Altitude	0.67	0.93 **	0.55	0.28	1.00 **	−0.36	−1.00 *	−0.52	−0.36	−0.36

Note: F.fruit—fresh fruit; B.fruit—browned fruit; O.Ferm—over-fermented. ** significantly different at α = 1%, * significantly different at α = 5%.

Table 3 showed that the presence of clay in the composition had a significant impact on enhancing the delicate floral aroma while simultaneously reducing the intensity of the meaty and overfermented aromas. The Zn content tended to strengthen dirty and weaken fine aromas, such as browned fruit, floral, and woody.

Agroclimatic conditions also played a crucial role in increasing the fine aroma. Both rainfall and altitude had similar effects on enhancing spiciness and decreasing the roasted aroma. Furthermore, altitude was found to be positively correlated with an increase in browned fruit aroma.

PCA analysis showed that sensory characteristics were strongly affected by the nutrient content of the soil (Figure 5). The aromatic characteristics found in cocoa beans from Soppeng were influenced by Ca, C, and C/N contents, as well as clay soil conditions. Meanwhile, the appearance of a fine aroma in MCC 02 and Sulawesi 1 beans from Pesawaran and MCC 02 from Pringsewu was impacted by Na content and sandy soil conditions.

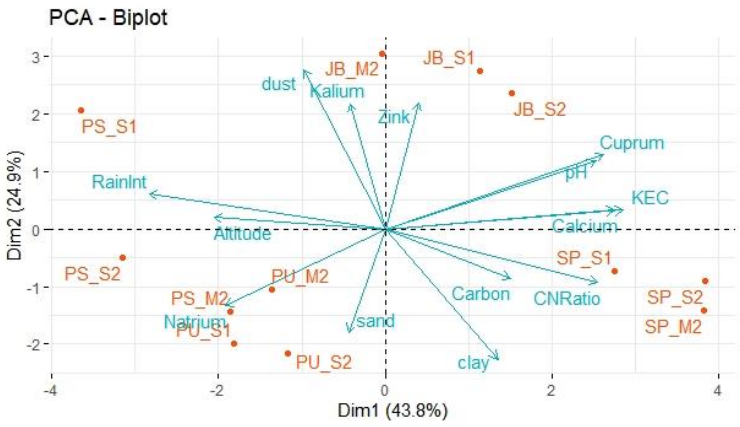


Figure 5. Clustering analysis of three cocoa genotypes based on flavor and nutrient components in four locations. Sul1—Sulawesi 1; Sul2—Sulawesi 2; MCC 02—location; JB—Jember; PR—Pesawaran; PU—Pringsewu.

4. Discussion

Indonesian cocoa genotypes have the potential to be developed into FFC products characterized by an aromatic flavor. The identification of sensory potential and genetic suitability for specific environments provides an opportunity to produce specialty cocoa products. This approach will facilitate optimal utilization of the opportunity to supply up to 10% of the total national production as FFC producers [6].

Previous studies reported that the flavor of cocoa beans at different locations varied based on genetic factors and the growing environment [10,17–20]. Genetic variation can influence factors such as bean size and color, pulp composition, and the content of volatile compounds [10], all of which contribute to the final flavor. Genotypic responses to the environment influence plant metabolic processes as well as the formation of both volatile and non-volatile metabolites. The differences in the genetic potential for volatile compounds were reported by Anita-Sari et al. [13], while environmental influences including climatic conditions, altitude, and plant management on the biochemical content of cocoa beans—both volatile and non-volatile compounds—were examined by Worku et al. [21]. In this study, the aromatic genotype consistently produced a fine aroma in different environmental conditions, while non-aromatic genotypes exhibited varying responses. Sulawesi 02 beans demonstrated more response to environmental changes and produced a fine aroma compared to those from Sulawesi 01.

Different approaches were observed for the Pesawaran and Soppeng samples, where both locations induced fine aroma in both aromatic and non-aromatic genotypes. The induction of fine aroma in Pesawaran was primarily influenced by agroclimatic conditions, while in Soppeng, soil conditions played a more crucial role. The altitude in Pesawaran affected fruit ripening and development, which influenced the formation of the final flavor. Plants grown at high altitudes require a longer ripening time, slower fruit development, and better flavor than those grown on low land [22]. Soil nutrient content had a significant impact on the formation of cocoa bean flavor. In addition to affecting plant growth and development, specific nutrients impact metabolic functions [23]. Soil composition is also known to affect the formation of plant yields. N, K, and Ca content play a crucial role in determining fruit quality [24], with K significantly affecting both biochemical and physiological processes. These nutrients serve a variety of functions in plants, particularly in tissues, acting as catalysts in various reactions and osmotic regulators [25]. According to Yadessa et al. [23], each nutrient affects plant growth, development, and yield quality by becoming integrated into organic compounds such as fatty, nucleic, and amino acids. These compounds, in turn, alter the chemical composition and sensory quality of the plant product. During plant development, nutrients accumulate in the fruit, making it a sink of minerals and carbohydrates [26] and contributing to the quality of the cocoa beans.

Environmental factors have a close relationship with the chemical characteristics that affect the sensory quality of cocoa beans [17,18]. Bitterness, acidity, and flavor were identified as the primary components of taste [27]. These attributes were strongly influenced by environmental factors in plant growth [17]. More specifically, the location of cocoa bean processing had a greater impact on acidity [28]. This result was in accordance with previous studies that examined environmental factors affecting the formation and intensity of fine aromas, such as fruity [17], floral, and nutty [27].

Volatile compounds determine the formation of aroma in cocoa beans but do not significantly impact taste [13]. These compounds are formed when the Maillard reaction and Strecker degradation occur during the roasting process. The intensity and composition of volatile compounds are largely determined by the content of sugar and amino acids [29,30]. Based on the results, non-aromatic genotype groups tended to be dominated by terpenoid and aldehyde content, while alkaloid, alcohol, and pyrazine compounds were more predominant in aromatic beans. According to Alvarez et al. [31], pyrazine compounds contribute significantly to the aroma of chocolate. This content was affected by climate, environmental conditions, pod ripeness, varieties, and processing [31]. Anita-Sari et al. [10] stated that each genotype of Indonesian cocoa exhibited different flavor characteristics,

both aromatic and non-aromatic. This phenomenon was influenced by the composition and intensity of the compounds in the beans.

The flavor similarity observed showed that genetic and environmental conditions contributed to flavor formation in cocoa beans. Genetic material with a premium flavor when grown in a different environment can undergo changes. This is because the flavor is very sensitive to alterations in the genetics and environment [32]. The strong aromatic characteristics of a genotype were influenced by environmental factors in both growing and processing environments [17,33], including bean origin, soil conditions, climate, fermentation methods, microbes, and post-harvest processes [28]. These results indicate that Indonesia has considerable potential, considering the diversity of cocoa genetics supported by the agro-climatic conditions in the development areas.

5. Conclusions

In conclusion, this study found that cocoa bean taste characteristics were influenced by both genetic factors and environmental conditions. Therefore, to cultivate specialty cocoa, the use of certain genotypes and environments conducive to the development of distinct aromatic qualities should be considered. Under specific environmental circumstances, including both agroclimatic factors and soil compositions, non-aromatic genotypes were found to produce aromatic cocoa beans. Based on the results, the formation of fine aroma was influenced by several factors, including the presence of carbon (C), the carbon-to-nitrogen ratio (C/N), sodium (Na), calcium (Ca), potassium (KEC), and copper (Cu), as well as certain soil conditions. The aromatic profile was primarily characterized by the presence of esters, furans, furanones, alcohols, and pyrazines.

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