UJEAS

UNIZIK JOURNAL OF ENGINEERING AND APPLIED SCIENCES

UNIZIK Journal of Engineering and Applied Sciences 5(1), June (2025), 2272 - 2281
Journal homepage: https://journals.unizik.edu.ng/index.php/ujeas
PRINT ISSN: 2992-4383 || ONLINE ISSN: 2992-4391

Effect of Copper-Based Fungicide on Chemical Composition of Cocoa Seeds

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Abstract
Production of cocoa seeds, one of Nigeria's major non-oil foreign exchange earners as well as a major raw material for the beverage industry, is greatly hindered by diseases caused by various species of the genus Phytophthora. To avert this, copper-based fungicides are sprayed on the leaves of cocoa trees to control or prevent the survival of this organism by the farmers without paying attention to the effects of this chemical on the proximate composition of cocoa seeds. This study therefore investigated the effects of a copper-based fungicide (Ridomil Gold Copper) on the quality of the cocoa seeds by spraying cocoa trees, including the pods, with 50.00 g/L of copper-based fungicide. The results obtained showed that cocoa seeds from the control trees showed significantly higher contents of fiber (4.51%), protein (15.1%), and fat (36.1%) when compared to the respective values of 3.45, 3.95, and 7.59% obtained for the cocoa seeds harvested from the fungicide-treated cocoa trees. All other proximate compositions did not show any statistical difference, except for carbohydrate and calorific values, which were significantly higher in cocoa seeds from fungicide-treated cocoa trees. Seeds from fungicide-treated trees showed significantly higher potassium, phosphorus, and magnesium contents but lower zinc and copper contents. However, phytochemicals such as phenols, alkaloids, flavonoids, and tannins were significantly lower in content in the seeds of fungicide-treated cocoa trees. The contents of glycosides and antioxidants in the cocoa seeds were statistically similar for both the control and treatment, except for ascorbic acid, which showed a significantly lower value (4.8 mg/100 ml) in cocoa seeds from fungicide-treated cocoa trees, compared with the value recorded for the control in this study (13.33%). The foregoing results showed that the use of copper-based fungicides for the control of black pod disease in cocoa adversely affected the quality of cocoa seeds from the treated trees.

Keywords: Copper-Based Fungicide, Chemical, Composition, Cocoa Seeds

1. Introduction

Cocoa (Theobroma cacao L.), is the primary raw material for numerous chocolate industries and is one of the most significant cash crops in the majority of the nations in the West and Central African sub-regions (primarily Cote d'Ivoire, Ghana, Nigeria, and Cameroon). Nigeria is the world's fifth-largest producer of cocoa behind Cote d'Ivoire, Ghana, Indonesia, and Cameroon (Abu et al., 2021). In terms of generating foreign exchange, generating revenue at the national level, and generating revenue for socioeconomic provision, cocoa as a crop boosts the economy of the nation where it is grown (Boysen et al., 2023). In Nigeria, cocoa plantations employ 300,000 farmers and the purchase of 800,000 hectares of land. Nigeria produced 328,263 tons of cocoa in 2017, which made up around 2% of the nation's exports. Ondo, Ogun, Osun, Oyo, and Ekiti are the cocoa-growing regions, and they account for 60% of the nation's total production (Bukola et al., 2021). Before 1970, Nigeria was the second-largest producer of cocoa in the world, but this position fell on account of significant amounts of crude oil that were discovered (Abdullahi et al., 2021).

The main problems facing cocoa seed production are pests and diseases, with Phytophthora pod rot or "black pod" being the most serious cocoa disease in Nigeria (Adeniyi, 2019). The disease is caused by Phytophthora palmivora and Phytophthora megakarya (Opoku et al., 2004), which accounts for about 30-100 % yield losses during outbreak (Ebaiarrey et al., 2024). The majority of fungicides used in Nigeria to treat this disease are copper-based fungicides (Tamm et al., 2022). Long-term usage of this fungicide has led to copper contamination of numerous cocoa farms across the country because soil microorganisms are unable to degrade copper (Manga et al., 2020). By the interaction between humic compounds and the oxides of Cu, Sn, and Fe, metal binding is a common occurrence in soil (Kulikova and Perminova, 2021). These heavy metal fractions, Fe, Sn, and Cu, along with their integrated oxides and organic matter complexes are thought to comprise the active component (Azeez et al., 2021). However, it has been shown that, for heavy metals, the most bioavailable and active forms are those that are exchangeable and soluble in water (Zhu et al., 2023). The term "bioavailability" refers to the chemicals released to living receptors, such as plant roots, from a medium of interest (Olaniran et al., 2013; Alengebawy et al., 2021). When soil has a high concentration of bio-available metals, it has a propensity to accumulate in the cocoa seeds, which will lower the quality of the product on the global market (Wade et al., 2022). Spraying copper-based fungicides on cocoa plants for the treatment or control of black pod disease is another practical way for copper to reach the cocoa seeds (Sowunmi et al., 2019). Several studies have examined the efficacy of copper-based fungicides in controlling black pod disease in cocoa and their potential to cause copper accumulation in soil and plant tissues, there remains a notable paucity of research specifically investigating their impact on the nutritional and phytochemical composition of cocoa seeds This study was aimed at determining the impact of copper-based fungicides on the nutritional and phytochemical compositions of cocoa seeds harvested from the treated trees.

2.0 Materials and methods

2.1 Study Area

This research was conducted in Adejubu town situated between Longitude 5°.5'1'' – 5° 29'39'' E and Latitude 7°3'40 – 7°26'38'' N in the Southeast of Akure North. It is bordered by Imafon District to the south and Baba-Sale District to the north. Adejubu town has several locations of lowlands and rough mountains with granite outcrops.

2.2 Field Work

The fieldwork was conducted on two cocoa farms randomly selected; one farm was used for the control experiment, while the other farm was sprayed with copper-based fungicide (Ridomil Gold Copper). To carry out the study, twenty (20) cocoa trees were chosen randomly on each of the farm sites. Twenty cocoa trees were treated with a copper-based fungicide on the experimental or treatment farm site, while twenty trees were not sprayed with a copper-based fungicide on the control farm site. The research work was carried out between July and October 2022.

2.2 Mineral Analysis

The procedures of the Association of Official Analytical Chemists (AOAC, 2005), were employed to determine the mineral content. Atomic absorption spectroscopy was used to determine the concentrations of Mg, Cu, Mn, Fe, Co, and Zn, while the concentrations of Ca, K, and Na were determined in triplicate using a flame photometer.

2.4 Proximate Analysis

AOAC procedures were followed for the proximate analysis (moisture, ash, fat, protein, and carbohydrate content, respectively) (AOAC, 2000). The thermogravimetric method was used to determine the content of ash and moisture; the Kjeldahl technique and soxhlet extraction technique were used to determine the protein and fat contents, respectively, while the amount of carbohydrates was calculated by difference. All analysis were carried out in triplicate.

2.5 Quantitative Phytochemical Analysis

Using standard protocols as stated by Onwuka (2005) and Oyedemi et al. (2010), the alkaloids, glycosides, saponins, phenols, flavonoids, and tannins contents of the cocoa seeds were determined.

2.6 Statistical Analysis

Data were analyzed by Analysis of Variance (ANOVA) at 95% Confidence Intervals, using Statistical Package of Social Sciences (SPSS) software version 20.0. Means were separated using Duncan Multiple Range Test (DMRT) at 5 % level of probability

3.0 Result and Discussion

3.1 Result

3.1.1 Effect of Copper-based Fungicide on Proximate Composition of Cocoa Seeds

As shown in Table 1, significant differences were observed in all the proximate compositions except for moisture and ash in this study. The recorded values for moisture and ash were higher in the cocoa seeds that were not sprayed with copper-based fungicide (control). The crude fiber, fat, and protein in the control had respective values of 4.61%, 36.10%, and 15.10% % which were statistically higher when compared to values recorded in the cocoa seeds from copper-based fungicide-treated cocoa trees. The fungicide-treated cocoa seeds had fat and protein content of 7.59% and 3.95% respectively which can be considered to be extremely low compared to the control, 36.10% and 15.10%, respectively. Cocoa seeds from cocoa trees sprayed with copper-based fungicide had carbohydrate value (56.00%) that was significantly greater than those recorded for cocoa seeds from the untreated cocoa trees (14.5%). The results of calorific value followed the same pattern as recorded for the carbohydrate content.

Table 1: Proximate composition of cacao seeds as influenced by copper-based fungicide

Proximate	Treatment (%)		t-test value
	Control (0.00)	Copper-based fungicide (50.00)	
Moisture	25.60±0.09^{a}	25.30±0.04^{a}	0.088
Ash	4.02±0.05^{a}	3.62±0.11^{a}	0.199
Crude fibre	4.61±0.04^{a}	3.54±0.07^{b}	0.004
Crude fat	36.10±0.06^{a}	7.59±0.03^{b}	<0.001
Protein	15.10±0.05^{a}	3.95±0.03^{b}	<0.001
Carbohydrate	14.54±0.08^{b}	56.00±0.19^{a}	<0.001
Energy (Kcal)	516.17±0.77^{b}	588.24±1.56^{a}	<0.001

Data were expressed as means ±SE of three replicates. The means within a row followed by the same superscripts are statistically the same at p≤0.05

3.1.2 Effect of Copper-based Fungicide on Macro - and Microelements Present in Cocoa Seeds

The effect of copper-based fungicide on the presence of macro and microelements in cocoa seeds is presented in Table 2. Spraying of copper-based fungicide significantly enhanced the contents of potassium (34.00 ppm), phosphorus (12.39 ppm), and magnesium (3.52 ppm), respectively, when compared to those recorded for the control (Table 2). A significant difference was observed in the contents of magnesium, potassium and phosphorus, while there was no significant difference in the calcium content of cocoa seeds in this study. Microelements such as copper, sodium and zinc were significantly higher in content in the cocoa seeds from the control than those in the seeds from treated cocoa trees. A significant difference was observed in the contents of copper and zinc, while all the other micro-elements did not show any statistical difference at p≤0.05. It should be noted that though the presence of cobalt was investigated in this study, it was absent in the cocoa seeds from both the treatments and controls.

Table 2: Macro and microelements of cocoa seeds as influenced by copper-based fungicide

Elements	Treatment (g/L)	t test –value

		Control (0.00)	Copper-based fungicide (50.00)	
Macroelements	Mg	3.13 ± 0.05^{b}	3.52 ± 0.01^{a}	<0.003
	Ca	0.10 ± 0.01^{a}	0.11 ± 0.01^{a}	0.225
	K	26.00 ± 1.00^{b}	34.00 ± 2.00^{a}	<0.005
	P	10.97 ± 0.08^{b}	12.39 ± 0.17^{a}	<0.010
Microelements	Cu	1.69 ± 0.07^{a}	0.22 ± 0.01^{b}	<0.001
	Mn	0.30 ± 0.00^{a}	0.30 ± 0.00^{a}	0.432
	Fe	0.35 ± 0.01^{a}	0.05 ± 0.00^{a}	0.386
	Na	3.24 ± 0.19^{a}	2.52 ± 0.17^{b}	0.071
	Co	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	-
	Zn	1.70 ± 0.07^{a}	0.87 ± 0.03^{b}	<0.001

Data were expressed as means ±SE of three replicates. The means within a row followed by the same superscript are statistically the same at $p \leq 0.05$

Magnesium concentration increased significantly from 3.13 ± 0.05 ppm in control seeds to 3.52 ± 0.01 ppm in treated seeds. Magnesium is central to chlorophyll and enzyme activation. This increase may result from a compensatory mechanism where copper-induced oxidative stress stimulates chloroplast development and Mg uptake for photosynthetic repair (Verbruggen et al., 2009). There was no significant difference in calcium content between control and treated seeds. Calcium plays a structural role in cell walls and membranes, and its uptake is often less influenced by micronutrient treatments due to its apoplastic transport pathway (White & Broadley, 2003). The stable levels suggest that copper-based fungicides do not interfere with Ca uptake in cocoa. Potassium increased from 26.00 ± 1.00 to 34.00 ± 2.00 ppm. This is a notable finding, as K is essential for osmoregulation and seed development. The increase could result from enhanced K translocation due to changes in root permeability or transporter activity under copper-induced stress (Broadley et al., 2012). Phosphorus also showed a significant increase. P is crucial for energy metabolism (ATP) and seed formation. Studies have shown that low-to-moderate levels of copper can stimulate phosphorus metabolism as plants attempt to maintain membrane integrity and energy balance under stress conditions (Kabata-Pendias, 2010). Cu levels was observed to drop from 1.69 ± 0.07 to 0.22 ± 0.01 ppm in seeds of treated plants. This is counterintuitive since the applied fungicide contains copper. This might be as a result leaching of copper beyond the root zone due to heavy rainfall (Alloway, 2013). Mn levels remained constant at 0.30 ppm. Mn is involved in redox processes and enzyme function, and its uptake shares similar pathways with iron and magnesium. The stability may be due to its limited mobility and low interaction with copper (White & Broadley, 2009). Iron content dropped slightly but not significantly. Fe and Cu often compete for uptake and transport proteins, but in this case, the fungicide dose may not have been high enough to cause major Fe displacement (Curie & Mari, 2017). It's also possible that the plant preferentially allocated Fe to vegetative tissues rather than seeds. Na showed a decreasing trend from 3.24 to 2.52 ppm, though not statistically significant. While sodium is not essential in most plants, in small amounts it may substitute for potassium in some physiological roles. The observed decrease might relate to increased K levels or possible changes in membrane transporters under copper exposure (Broadley et al., 2012).

3.1.3 Effect of Copper-based Fungicide on Phytochemical Constituents of the Cocoa Seeds

The phytochemical analysis reveals that copper-based fungicide application significantly influenced the concentrations of several key secondary metabolites in cocoa seeds. Alkaloid content was significantly reduced (from 0.182 g/L to 0.084 g/L; $p < 0.001$), suggesting a suppression of nitrogen-based secondary metabolism, which may be linked to copper's interference with nitrogen assimilation pathways or oxidative stress responses (Sharma & Agrawal, 2005). Similarly, flavonoid and tannin levels declined markedly ($p = 0.003$ and <0.001, respectively), potentially due to copper-induced inhibition of the phenylpropanoid pathway, which governs the biosynthesis of these antioxidant compounds (Ullah et al., 2015). In contrast, phenol content increased significantly ($p = 0.010$), likely as a defense response, since phenols play a key role in plant stress resistance and lignification under heavy metal exposure (Parrotta et al., 2015). Interestingly, saponin and glycoside levels remained statistically unchanged, indicating selective pathway sensitivity to copper. These findings align with studies showing that heavy metals, particularly copper, can variably affect phytochemical biosynthesis depending on compound class and stress intensity (Fones & Preston, 2013). Overall, the results suggest that copper fungicide alters the phytochemical profile of cocoa seeds, potentially impacting their nutritional, medicinal, and organoleptic qualities.

Table 3. Phytochemical constituents (µg/ml) of cocoa seeds as influenced by copper-based fungicide

Phytochemical	Treatment g/L		t- test value
	Control (0.00)	Copper-based fungicide (50.00)	
Alkaloids	0.182±0.03[a]	0.084±0.04[b]	<0.001
Glycosides	0.418±0.67[a]	0.380±0.01[a]	0.631
Saponins	0.426±0.03[a]	0.399±0.05[a]	0.010
Phenols	11277.68±436.53[b]	14252.32±145.71[a]	0.010
Flavonoids	1291.30±39.97[a]	676.81±7.23[b]	0.003
Tannins	1858.55±8.73[a]	1210.45±0.91[b]	<0.001

Data were expressed as means ±SE of three replicates. The means within a row followed by the same superscript are statistically the same at $p \leq 0.05$

3.1.4 Effect of Copper-based Fungicide on Vitamins Content of Cocoa Seeds

The results (Table 4) showed that the levels of important vitamins in cocoa seeds were considerably decreased by applying a copper-based fungicide at a rate of 50 g/L. A substantial inhibitory impact was indicated by the marked drop in ascorbic acid content from 13.33 ± 0.67 mg/100 g in the control to 4.80 ± 0.40 mg/100 g in treated seeds ($p = 0.002$). The levels of lycopene and β-carotene also decreased significantly, going from 0.22 ± 0.001 mg/100 g to 0.15 ± 0.0007 mg/100 g ($p < 0.001$) and 0.33 ± 0.02 mg/100 g to 0.20 ± 0.0004 mg/100 g ($p = 0.011$), respectively. Enzymatic processes involved in vitamin production, especially those in the carotenoid and ascorbate-glutathione cycle, are known to be hampered by oxidative stress (Hasanuzzaman et al., 2020). These results highlight the need for balanced fungicide use in cocoa production systems to maintain nutritional integrity.

Table 4: Vitamins (mg/100ml) of cocoa seeds as influenced by copper-based fungicide

Vitamin	Treatment (g/L)		t-test value
	Control (0.00)	Copper-based fungicide (50.00)	
Ascorbic acid	13.33 ± 0.67[b]	4.80 ± 0.40[b]	0.002
Lycopene	0.22 ±0.001[a]	0.15 ± 0.0007[a]	<0.001
B- carotene	0.33 ±0.02[a]	0.20 ± 0.0004[a]	0.011

Data were expressed as means ±SE of three replicates. The means within a row followed by the same superscript are statistically the same at $p \leq 0.05$

3.2 Discussion

The proximate composition analysis showed that the percentage moisture content in the control seeds was higher than that of the treated seeds. The percentage moisture content obtained in this study (25.30±0.04%), disagrees with the results of Djali et al. (2023), who reported moisture content of 14.14 % in fresh cocoa and 7.86% in roasted cocoa as well as those of Afoakwa et al. 2013 and Adeyeye (2013), who reported an average of 4.43% and 6.65% in unfermented cocoa and natural cocoa powder respectively. Excessive moisture content can make a cocoa seed lose its flavor and deteriorate because it is hygroscopic in nature.

The percentage ash content in the control seeds is numerically higher than that of the treated seeds, which aligns with the reports of Afoakwa et al (2013) and Djali et al (2023), who reported 4.27 % and 3.2%, respectively. The percentage of crude fiber in the experimental seeds is lower than that of the control seeds. The level of crude fat as reported in this study disagrees with the reports of Afoakwa et al. (2013) who reported an average crude fat of 53.33%, but aligns with Djali et al. (2023), who reported an average crude fat of 4.20% in fresh cocoa.

The percentage of crude fat reported in this study disagrees with the study of Adeyeye (2013), who reported 14.5 %. The percentage of carbohydrates as reported in this study aligns with that of Djali et al. (2023), who reported an average carbohydrate of 43.26% in fresh cocoa, and that of Adeyeye (2013), who also reported 48.9% carbohydrate content in natural cocoa powder, while it disagrees with the results of Afoakwa et al. (2013), who reported an average carbohydrate content of 18.43% in unfermented cocoa. Carbohydrate plays a vital role in the building up of energy. It also provides immediate energy unlike other classes of food (Afoakwa et al. 2013). The crude protein content observed in this study disagrees with the study of Afoakwa et al. (2013), who reported an average protein content of 20.63%. This is an indication that the copper-based fungicides might interfere with the accumulation of protein in the seeds (Assareh et al., 2018).

The components present in the growing soil and the potential availability of nutrients from the application of different fungicides during the growth process have a significant impact on the presence of macro and microelements in cocoa (Assa et al., 2019). Potassium was the most abundant mineral in cocoa seeds in this study as compared to the other minerals. This observation goes in line with the reports of Afoakwa et al. (2013). The presence of micronutrients is necessary for the maintenance of certain physiochemical processes that are essential to life (Duru, 2020).

The concentration of calcium reported in this study disagrees with the studies conducted by Adeyeye (2013), Assa (2019), and Afoakwa et al. (2013), who reported concentrations of 1.02, 2.34 and 145.58 mg/100g, respectively. Calcium works as a constituent of bone and teeth, a source of regulation of nerve and muscle function. It is necessary for the conversion of prothrombin to thrombin during blood coagulation25. The concentration of phosphorus observed in this study is higher than what was reported by Adeyeye (2013), who reported 5.80 mg/100 g in natural cocoa powder, but lower than the concentration reported by Afoakwa et al. (2013), who reported an average concentration of 293 mg/100g in unfermented cocoa seeds. The potassium content reported in this study is far lower than that of Afoakwa et al. (2013), who reported 2,347.73 mg/100 g, but higher than the concentration of 2.39 mg/100 reported by Assa et al. (2019). Potassium helps in acid-base balance, regulation of osmotic pressure, conduction of nerve impulses and muscle contraction and it also helps in glycogenesis. High potassium content leads to dilation of the heart, cardiac arrest, small ulcers, paralysis, and muscular weakness (Upadhaya and Kim, 2020). Potassium and phosphorus have the highest concentrations in this study, with the concentration of potassium being twice as much as that of phosphorus (Table 2). The concentration of magnesium obtained in this study aligns with the report of Adeyeye (2013) who also reported a concentration of 3.13 mg/100 g, but disagrees with a concentration of 286 mg/100 g reported by Afoakwa et al. (2013).

A potent class of substances found in plants' secondary metabolites, phytochemicals contain a wide variety of chemical substances like polyphenols, saponins, tannins, flavonoids, alkaloids and glycoside (Murray et al., 2000, Rusconi and Conti, 2010). Phytochemical analysis (Table 3), shows that the percentage of glycoside in the control seeds is higher than that of the experimental bean. The concentration of tannin in the control seeds is greater than that of the experimental seeds. There is a higher percentage of alkaloids and saponins in the control seeds than in the treated seeds. These results are in agreement with those of Kumah et al. (2023); they also reported higher percentage of phenols in ethylacetate-purified cocoa leaf extracts, compared to the other phytochemicals. Saponin helps to reduce blood cholesterol and it is used as an antioxidant, helping to reduce the risk of cancer (Kayaputri et al. 2020).

The level of Vitamin C in the control seeds is higher than that of the treated seeds. High levels of Vitamin C leads to bleeding of the gum. Vitamin C is an essential nutrient that helps to repair worn-out tissues and production of certain enzymes Bechara et al. 2022). The concentrations of lycopene and β-carotene in the control seeds were higher than those in the treated seeds. These results align with the results of Nascimento da Silva et al. (2014), who reported 10.90 mg/L of ascorbic acid in cocoa honey. This further indicated that the consumption of cocoa beans treated copper-based fungicide might limit the functionality of these chemicals as potential antioxidants that help to protect humans against heart disease and certain types of cancer. Aikpokpodion et al. (2010), also reported that the excessive presence of copper can cause oxidative stress in plants and also cause an increase in antioxidant response due to increased production of highly toxic oxygen free radicals. Thus, at high concentrations, copper can become extremely toxic resulting in the yellowing of leaves and premature death of cells in the living tissues of young plants. At the cellular level, toxicity may result from the binding to sulfhydryl groups in proteins.

Generally, biochemical changes observed in cocoa seeds following treatment with copper-based fungicide reveal a pattern consistent with copper-induced physiological stress in plants. Notably, macroelements such as potassium (K), phosphorus (P), and magnesium (Mg) significantly increased, while microelements such as copper (Cu) and zinc (Zn) decreased drastically. The substantial drop in seed Cu levels is particularly striking, considering the fungicide contains copper. This paradox may be due to metal detoxification or exclusion mechanism in the plant, such as the sequestration of excess Cu in root vacuoles or binding with organic ligands, thereby preventing translocation to seeds (Mathur and Chauhan, 2020).

Phytochemically, a significant reduction was observed in flavonoids, tannins, and alkaloids — compounds that play critical roles in plant antioxidant defence and metabolic regulation. Copper-induced oxidative stress disrupts biosynthetic enzymes and impairs secondary metabolite production (Shabbir et al., 2020). Interestingly, phenol levels were elevated in treated seeds, possibly reflecting a compensatory stress response, as phenolics are commonly upregulated during metal stress to scavenge reactive oxygen species (ROS). On the other hand, the marked decline in ascorbic acid, β-carotene, and lycopene further supports the hypothesis of copper-induced oxidative damage, since these vitamins are highly sensitive to redox imbalance and can be degraded under stress conditions (Miazek et al., 2020).

In human beings, the absorption of copper in the alimentary tract affects the rate of digestion and some other chemical reactions of the body system. Copper affects the reproduction and growth of plants and animals. Sperm motility also appears to be compromised by the presence of copper in human spermatozoa which either leads to low sperm count or the absence of sperm (Yanus et al. 2014). The high concentration of copper also reduces the longevity of some organs in the human body causing chronic diseases. Wilson's disease patients have been shown to exhibit copper toxicity (a hereditary illness in which copper builds up in the body). Usually, there is a connection between the liver and the brain. Symptoms of the liver include weakness, vomiting, swelling in the legs, abdominal fluid accumulation, yellowing of the skin, and itching. Tremors, muscle stiffness, difficulty speaking, personality changes, anxiety, and the ability to see or hear things that others do not are among the symptoms associated with the brain. Some other examples of Wilson disease include cirrhosis of the liver (inflammation of the liver), and temperamental behavior (Soetan et al. 2010). It also results in the damage of some organs such as the liver and the kidney due to the high consumption of copper in cocoa products Sager, 2012).

4.0 Conclusion

The finding of this study has established that copper-based fungicide (Ridomil gold copper) may not necessarily lead to the accumulation of copper in cocoa beans but may adversely affect the quality of cocoa beans. The application of copper-based fungicide significantly alters the biochemical composition of cocoa seeds, with implications for both nutritional quality and plant physiological health. While certain macroelements such as potassium, phosphorus, and magnesium increased, essential microelements like zinc and copper were markedly reduced, likely due to metal exclusion or antagonistic uptake interactions induced by excess copper. Additionally, the observed decline in key phytochemicals (flavonoids, tannins, and alkaloids) and antioxidant vitamins (ascorbic acid, β-carotene, and lycopene) indicates oxidative stress and disruption of normal metabolic functions. These changes reflect known physiological effects of copper toxicity, including nutrient imbalance, impaired antioxidant defense, and biosynthetic inhibition. Therefore, while copper-based fungicides remain essential in controlling fungal diseases such as black pod, their long-term or high-dose application may compromise cocoa seed quality. A more balanced and controlled use of such fungicides is recommended to preserve the nutritional and phytochemical integrity of cocoa, especially when seeds are intended for consumption or breeding purposes.

5.0 Recommendation

Future studies should investigate the mechanisms of copper uptake, transport, and sequestration in cocoa plants to better understand why copper levels decreased in seeds despite external application. Future research should aloo focus on optimizing copper-based fungicide application strategies to balance disease control efficacy with minimal biochemical disruption in cocoa plants, and to determine the threshold levels of copper that can be safely applied without inducing nutrient antagonism or oxidative stress.

Acknowledgements

The authors acknowledge the management of the Kwara State University, Malete and University of Ilorin, for providing enabling environment for the conduct of this research work

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