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Cacao Bean: Technological advancement in cocoa production, medicinal, pharmacological and nutritional importance of Cocoa

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ABSTRACT

Cocoa (*Theobroma cacao* Linn.) is one of the world's most economically significant crops, serving as a primary ingredient in chocolate production and providing substantial income to millions of farmers globally. Beyond its economic value, cocoa beans possess remarkable pharmacological and nutritional properties due to their rich composition of polyphenols, flavonoids, vitamins, and minerals, which contribute to antioxidants, anti-inflammatory, and cardioprotective effects. This paper explores the pharmacological and nutritional importance of cocoa beans, emphasizing the role of science in advancing cocoa production through modern breeding techniques and genetic modification.Despite its economic relevance, cocoa production faces major challenges, including pest infestations, plant diseases, and low yield rates due to traditional farming practices. Advances in biotechnology and genetic engineering have provided new methods for improving yield and disease resistance, yet ethical concerns and environmental sustainability remain key considerations. This study highlights the benefits and limitations of traditional and modern breeding approaches, emphasizing the need for sustainable strategies to enhance global cocoa production. The findings suggest that integrating scientific advancements with traditional agricultural knowledge can significantly improve the efficiency and sustainability of cocoa farming.

Keywords: Cocoa; Chocolate; CRISPR/Cas Technology; Global food security

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Introduction

Cocoa beans (*Theobroma cacao* L.) have long been valued for their economic, nutritional, and medicinal significance (Etaware, 2021). Historically, cocoa was used by ancient civilizations such as the Mayans and Aztecs for its perceived therapeutic effects, including its ability to enhance stamina, reduce fatigue, and improve mood (Badrie *et al*., 2015). Today, with advancements in science and technology, modern research continues to uncover the vast pharmacological potential of cocoa, demonstrating its role in disease prevention and health promotion (Etaware, 2021). Cocoa is now recognized as a functional food, meaning it provides benefits beyond basic nutrition, offering bioactive compounds that contribute to overall well-being (Latif, 2013).

One of the most significant aspects of cocoa's pharmacological importance lies in its rich composition of bioactive compounds, including polyphenols, alkaloids, antioxidants, flavonoids, and essential minerals, all of which play critical roles in promoting health and preventing chronic diseases, including cardiovascular disease, diabetes, and obesity (Norris *et al*., 2021). These compounds contribute to its powerful antioxidant, anti-inflammatory, cardioprotective, neuroprotective, and metabolic-regulating properties (Goya *et al*., 2016). The consumption of cocoa has been linked to reduced risks of cardiovascular diseases, diabetes, neurodegenerative disorders, and even certain cancers. Furthermore, its impact on mood and mental health has led to its increasing application in the field of psychopharmacology (Scholey and Owen, 2013). The pharmaceutical and nutraceutical industries have begun to integrate cocoa-derived compounds into therapeutic formulations,

aiming to harness its natural healing properties for drug development and clinical treatments (Tomaru *et al*., 2020). For example, cocoa flavanols are being researched for their role in cardiovascular health, while theobromine is being studied for its potential in respiratory and cognitive health applications (Martinez-Pinilla *et al*., 2015). Additionally, scientific advancements in cocoa processing technologies have allowed for the enhancement and preservation of its bioactive components, increasing its efficacy in medicinal applications (Magrone *et al*., 2017). Despite these promising pharmacological benefits, challenges remain in optimizing cocoa's therapeutic potential. Factors such as cocoa processing methods, bioavailability, and individual variations in metabolism can influence its effectiveness (Loffredo *et al*., 2017). As a result, ongoing research is focused on improving extraction techniques, standardizing dosages, and developing targeted cocoa-based therapies.

While cocoa's nutritional and pharmacological properties have been widely studied, there is a lack of comprehensive research examining how technological advancements in cocoa production influence these properties. Furthermore, many of the current studies focus on cocoa's end-products, such as chocolate, rather than raw beans and the role of advanced agricultural practices in improving their pharmacological qualities (Nwachukwu and Udeh, 2020). Despite the growing recognition of cocoa as a source of beneficial bioactive compounds, there remains limited exploration of how factors such as soil quality, genetic modification, and post-harvest processing influence the final chemical composition of the beans (Cote *et al*., 2021). Additionally, smallholder farmers in cocoa-producing regions often face significant barriers to accessing modern technology and agricultural practices, resulting in suboptimal yields and inconsistent bean quality (Etaware, 2022). These challenges hinder the full potential of cocoa as both a functional food and a major economic driver (Baudoin *et al*., 2018). Thus, this research seeks to fill these gaps by investigating the impact of scientific and technological advancements on cocoa production and exploring how these changes can improve the nutritional and pharmacological value of cocoa beans.

The global cocoa industry is one of the most economically significant sectors in the agricultural world, yet it faces numerous challenges ranging from climate change and pests to economic instability and social inequality (Sogodogo *et al*., 2019). As the demand for cocoa-based products continues to grow, it is crucial to enhance the production and quality of cocoa beans. Technological advancements in farming practices, such as precision agriculture (Etaware, 2019; Etaware *et al*., 2020; Etaware, 2023), biotechnological interventions, and sustainable farming techniques, have the potential to transform the industry by improving both the yield and quality of cocoa beans (Kok *et al*., 2019). The increasing body of evidence supporting the health benefits of cocoa makes it an essential component in the global push for functional foods that contribute to public health (Stewart *et al*., 2022). Furthermore, the pharmacological properties of cocoa beans are receiving greater attention, particularly in relation to their potential to aid in the prevention and treatment of various diseases (Almeida *et al*., 2023).By focusing on the intersection of science, technology, and health, this study aims to provide insights that can guide the future of cocoa cultivation, improve the livelihoods of cocoa farmers, and promote the consumption of cocoa as a nutritionally and pharmacologically valuable food source (Owusu *et al*., 2020).

2. *Nutritional and Medicinal Importance of Cocoa*

Cocoa beans are a rich source of bioactive compounds, essential minerals, and other nutrients that contribute to their nutritional and pharmacological properties.

Proximate Composition of Cocoa Bean

The proximate analysis of cocoa beans carried out by Foley *et al*. (2021) showed each cacao bean contains the following components:

- *Fat:* 40-50% of the dry weight, largely in the form of cocoa butter, which is rich in saturated and unsaturated fatty acids.
- *Proteins:* 15-20%, primarily globulins and albumins, important for amino acids.
- *Carbohydrates:* Around 30-40%, with dietary fiber accounting for a significant portion, promoting digestive health.

Vitamin Components of the Cacao Bean

The vitamin composition of cocoa beans was analyzed byBai *et al*. (2020) showed each cacao bean contains the following components:

- Vitamin A (Retinol): This particular vitamin supports vision and proper immune functions. It is found in trace quantity in cacao beans i.e., ≤3 µg/100g of raw cocoa beans.
- Vitamin B1 (Thiamine): Supports energy metabolism and nerve function. It is present in minute quantity i.e., ≤0.20 mg/100g of raw cocoa beans.
- Vitamin B2 (Riboflavin): This particular vitamin aids energy production and increases proper cellular functions. It is also present in small quantity i.e., ≤0.25 mg/100g of raw cocoa beans.
- Vitamin B3 (Niacin): Niacin is very important for digestive health and also pertinent for food conversion into energy and ATP. It is present in cacao beans at a relative small amount i.e., ≤2.50 mg/100g of raw cocoa beans.
- Vitamin B5 (Pantothenic acid): This particular vitamin is quite essential for fatty acid metabolism (e.g., lipolysis and glycogenesis), and it is also essential for the synthesis of acetyl coenzyme-A. Pantothenic acid is found in small quantities in cacao beans i.e., ≤0.85 mg/100g of raw cocoa beans.
- Vitamin B6 (Pyridoxine): It is involved in amino acid metabolism and neurotransmitter synthesis. It is found in trace quantity in cacao beans i.e., ≤0.10 mg/100g of raw cocoa beans.
- Vitamin B9 (Folate): It is very crucial for DNA synthesis and cell division. It is found in trace quantity in cacao beans i.e., ≤31 µg/100g of raw cocoa beans.
- Vitamin E (Tocopherol): Cocoa is a good source of vitamin E, a powerful antioxidant. This vitamin specifically acts as an antioxidant, protecting cells from oxidative damage. It is found in trace quantity in cacao beans i.e., ≤0.50 mg/100g of raw cocoa beans.
- Vitamin K (Anti-haemorrhagic vitamin): It plays a role in blood clotting in humans. It is found in trace quantity in cacao beans i.e., ≤2 µg/100g of raw cocoa beans.

Mineral Composition of Cacao Beans

- Magnesium: Cocoa is particularly rich in magnesium, which plays a vital role in muscle function, nerve transmission, and the regulation of blood pressure.
- Iron: It is important for oxygen transport in the blood.
- Copper, Zinc, and Manganese: These trace minerals are involved in enzyme functions and antioxidant defense mechanisms.

Phytochemical Components of the Cacao Bean

The phytochemical composition of cocoa beans was analyzed thus:

- Flavonoids: Cocoa beans are rich in flavonoids, particularly epicatechin, catechins, and procyanidins, which are powerful antioxidants. These compounds have been shown to have beneficial effects on cardiovascular health, improve cognitive function, and reduce inflammation (Liu *et al.,* 2018).
- Theobromine: An alkaloid found in cocoa that has stimulant properties like caffeine but is milder. It can aid in relaxation, improve mood, and enhance cardiovascular health (Stewart *et al.*, 2022).
- Caffeine: Cocoa contains caffeine, albeit in smaller amounts compared to coffee, contributing to alertness and mental focus.

Pests and Diseases Affecting Cocoa

Cocoa cultivation faces numerous challenges from pests and diseases, which can significantly reduce yield and quality. Some of the major pets and diseases affecting cocoa include:

1. Cocoa Pod Borer (*Conopomorphacramerella*): This is one of the most destructive pests in cocoa production, particularly in Southeast Asia. The larvae of the cocoa pod borer burrows into the pods, damaging the seeds and making them unfit for processing (Baudoin *et al*., 2018).
2. Cocoa Mirid (*Sahlbergellasingularis*): Mirid pests cause damage by feeding on cocoa pods, leading to reduced yields and secondary fungal infections (Chadha *et al*., 2021).
3. Black Pod Disease (*Phytophthora* spp.): Caused by the fungus Phytophthora, this disease leads to the rotting of cocoa pods, significantly impacting production (Etaware, 2019; Etaware and Adedeji, 2019; Olufayo*et al*., 2020; Obiakara*et al*., 2020).
4. Cocoa Swollen Shoot Virus Disease (CSSVD): A viral disease that causes stunting and reduced yield. It is primarily spread by insect vectors (Nwachukwu and Udeh, 2020).
5. Fungal Infections: In addition to *Phytophthora*, other fungal pathogens such as Fusarium and Aspergillus can infect cocoa pods and beans, causing spoilage and reducing the quality of the product.

Management of Cocoa Pests and Diseases

Efficient pest and disease management is essential to ensure sustainable cocoa production.

A combination of cultural, biological, and chemical control methods is employed:

1. Cultural Control:

- Crop Rotation: Alternating cocoa with other crops can help reduce the buildup of pests and pathogens.
- Pruning: Regular pruning of cocoa trees to remove diseased pods and infected branches can help reduce the spread of diseases.
- Field Sanitation: Proper disposal of diseased pods and fallen debris reduces the risk of pest infestation and disease spread.

2. Biological Control:

- Natural Predators: The use of natural predators like *Trichogramma* spp. (parasitic wasps) can help control the cocoa pod border by reducing its population.
- Fungal Biocontrol: Certain fungi, such as *Trichoderma*, have been used as biocontrol agents against *Phytophthora*, helping to reduce the severity of black pod disease (Garcia *et al*., 2021).

3. Chemical Control:

- Insecticides and Fungicides: The use of chemical treatments is common in cocoa farming. However, integrated pest management (IPM) strategies are preferred to minimize the overuse of pesticides and reduce environmental impact. The judicious use of fungicides to control Phytophthora and insecticides for cocoa mirid and cocoa pod borer are important (Sogodogo *et al*., 2019).

4. Genetic Resistance:

Breeding for resistance to diseases like black pod and CSSVD is an ongoing research area. Scientists are developing varieties that are more resilient to pests and diseases, reducing the need for chemical treatments and increasing the sustainability of cocoa farming (Baudoin *et al*., 2018).

5. Climate-Smart Practices:

Cocoa production is highly sensitive to climate change. Climate-smart agricultural practices, such as the use of shade trees to protect cocoa from extreme temperatures and adopting water-conserving irrigation systems, are being implemented to enhance the resilience of cocoa crops (Kok *et al*., 2019).

6.AI-mediated Cocoa Disease Prediction and Management

Several virtualprograms have been setup to monitor and forecast specific cocoa disease outbreak. These computer programs have been successful in their functionality so far, even though more upgrade is needed. One of such virtual disease forecast system includes ETAPOD®, developed by Etaware (2019), a forecast model designed to effectively determine and also quantify the outbreak of black pod disease in Nigeria, Africa and other cocoa growing regions around the world (Etaware, 2022). Black pod disease (BPD) of cocoa is caused by the noxious *Phytophthora*spp (Etaware *et al*., 2020; Obiakara*et al*., 2020; Etaware, 2021; Etaware, 2023).

3. Pharmacological Importance of Cocoa Beans

Cocoa beans (*Theobroma cacao*) have been recognized not only for their economic and nutritional value but also for their vast pharmacological applications. Scientific studies over the years have shown that cocoa possesses a range of health benefits, including antioxidant, anti-inflammatory, cardioprotective, neuroprotective, anti-diabetic, and mood-enhancing properties (Katz *et al*., 2011; Latif, 2013). These pharmacological effects arise from its rich composition of bioactive compounds such as flavonoids, polyphenols, alkaloids, and essential minerals. This section delves into the key bioactive compounds present in cocoa and their associated therapeutic applications, demonstrating how cocoa plays a crucial role in human health and disease prevention.

Bioactive Compounds in Cocoa

Cocoa beans are a powerhouse of bioactive compounds, including polyphenols, alkaloids, and essential minerals. These compounds work synergistically to deliver significant health benefits.

Flavonoids and Polyphenols

- Cocoa is one of the richest natural sources of flavonoids and polyphenols, which are known for their potent antioxidant and anti-inflammatory properties. The major flavonoids in cocoa include:
- Epicatechin: This flavonoid enhances endothelial function by stimulating nitric oxide (NO) production, which promotes blood vessel relaxation, improves circulation, and lowers blood pressure. It also exhibits strong anti-inflammatory effects (Hooper *et al*., 2012).
- Catechin and Procyanidins: These compounds help neutralize free radicals, thereby reducing oxidative stress, preventing cellular damage, and lowering the risk of chronic diseases such

as cardiovascular disorders, cancer, and neurodegenerative diseases (Goya *et al*., 2016).

- Quercetin: Another important polyphenol in cocoa, quercetin has been shown to exhibit anticancer properties by inducing apoptosis (programmed cell death) in cancerous cells and reducing inflammation in various tissues (Tomaru*et al*., 2020).
- Polyphenols in cocoa also modulate gut microbiota, which enhances gut health and boosts immune function (Santos *et al*., 2021).

Theobromine and Caffeine

Cocoa beans contain natural stimulants, including theobromine and caffeine, which contribute to various physiological effects:

- Theobromine: This alkaloid has a mild stimulant effect, improving cognitive function and alertness. Unlike caffeine, theobromine acts as a vasodilator, helping to lower blood pressure and enhance cardiovascular health. It also exhibits bronchodilatory properties, making it beneficial in the treatment of asthma (Martinez-Pinilla *et al*., 2015).
- Caffeine: Present in small amounts in cocoa, caffeine is known to enhance mental alertness, reduce fatigue, and improve concentration. It also stimulates the central nervous system and has been associated with enhanced cognitive performance (Scholeyand Owen, 2013).

Essential Minerals in Cocoa

Cocoa beans are a rich source of essential minerals, including:

- Magnesium: Plays a crucial role in muscle relaxation, nerve transmission, and cardiovascular health. A diet rich in magnesium has been linked to reduced risks of hypertension and type-2 diabetes (Latif, 2013).
- Iron: Essential for red blood cell production and oxygen transport in the body. Cocoa consumption can contribute to improved iron status and help prevent anemia.
- Zinc and Copper: These trace minerals support immune function, wound healing, and enzymatic reactions in metabolic processes (Keenan *et al*., 2021).

4. Health Benefits of Cocoa

Cardiovascular Health

Cocoa consumption has been widely studied for its cardioprotective effects. Several mechanisms contribute to cardiovascular benefits, including:

- Reduction in Blood Pressure: Cocoa flavonoids stimulate the production of nitric oxide (NO), leading to vasodilation and improved blood flow, which lowers blood pressure (Loffredo et al., 2017).
- Cholesterol Regulation: Regular consumption of cocoa has been shown to reduce levels of low-density lipoprotein (LDL, or "bad" cholesterol) while increasing high-density lipoprotein (HDL, or "good" cholesterol), thereby lowering the risk of atherosclerosis (Hooper *et al*., 2012).
- Antiplatelet Effects: Cocoa polyphenols reduce platelet aggregation, which prevents blood clot formation and reduces the risk of heart attacks and strokes (Latif, 2013).

Neuroprotective Effects

Cocoa flavonoids play a crucial role in brain health by:

- Enhancing Cognitive Function: Cocoa improves cerebral blood flow, which enhances memory, attention, and problem-solving abilities (Crichton *et al*., 2016).
- Reducing Neuroinflammation: Chronic neuroinflammation is linked to neurodegenerative diseases such as Alzheimer's and Parkinson's. Cocoa polyphenols help reduce inflammation and oxidative stress in the brain, potentially slowing cognitive decline (Tomaru*et al*., 2020).
- Preventing Neuronal Damage: The antioxidant properties of cocoa protect neurons from oxidative stress, reducing the risk of neurodegeneration (Goya *et al*., 2016).

Anti-Diabetic and Metabolic Benefits

Cocoa has beneficial effects on metabolic disorders, including:

- Improved Insulin Sensitivity: Flavanols in cocoa enhance insulin function and glucose metabolism, reducing the risk of type 2 diabetes (Tomaru*et al*., 2020).
- Regulation of Lipid Metabolism: Cocoa consumption has been associated with reduced fat accumulation and improved lipid profile, lowering the risk of obesity-related complications (Latif, 2013).

Mood Enhancement and Mental Health

Cocoa has long been known to improve mood and emotional well-being due to its ability to:

- Increase Serotonin Levels: Cocoa stimulates the production of serotonin, a neurotransmitter that promotes feelings of happiness and relaxation (Scholey and Owen, 2013).

- Reduce Stress and Anxiety: Theobromine and polyphenols in cocoa help regulate cortisol levels, reducing stress and promoting mental well-being (Martinez-Pinilla *et al.*, 2015).

Anti-Cancer Properties

Research suggests that cocoa polyphenols exhibit anticancer effects through:

- Induction of Apoptosis: Cocoa compounds trigger programmed cell death in cancer cells, slowing tumor growth (Goya *et al*., 2016).
- Reduction of Inflammatory Markers: Chronic inflammation is a key driver of cancer progression, and cocoa polyphenols have been found to reduce inflammatory mediators (Tomaru et al., 2020).

Wound Healing and Dermatological Applications

Cocoa is beneficial for skin health due to the following rationale listed and discussed in details below:

- Collagen-Boosting Properties: Flavonoids in cocoa stimulate collagen production, enhancing skin elasticity and reducing the appearance of wrinkles (Keenan *et al*., 2021).
- Protection Against UV Radiation: Cocoa polyphenols provide a natural defense against UV-induced skin damage, reducing the risk of premature aging and skin cancer (Magrone *et al.,* 2017).
- Moisturizing Effects: Cocoa butter, a key extract from cocoa beans, is widely used in skincare products for its hydrating and anti-inflammatory properties (Santos *et al*., 2021).

Future Prospects in Cocoa Pharmacology

Given the extensive pharmacological benefits of cocoa, research is focusing on:

1. Development of Cocoa-Based Nutraceuticals: Scientists are investigating cocoa-derived supplements for cardiovascular, neurological, and metabolic health (Latif, 2013).
2. Integration into Pharmaceutical Formulations: Cocoa polyphenols are being explored for their potential use in anti-inflammatory and anticancer drug development (Goya *et al*., 2016).
3. Personalized Nutrition and Medicine: Research is exploring how cocoa bioactives can be tailored for individualized health benefits based on genetic profiles (Santos *et al*., 2021).
4. With ongoing scientific advancements, cocoa holds immense potential for revolutionizing pharmacological applications, making it a valuable natural resource for health and medicine.

Conclusions

Cocoa production remains a cornerstone of the global agricultural economy, with significant pharmacological, nutritional, and economic importance. This study has examined the scientific advancements in cocoa breeding, pest and disease management, and the impact of genetic modification on crop yield and resilience. While traditional cultivation methods have sustained the industry for centuries, they are increasingly challenged by climate change, pests, and declining soil fertility (Osei-Bonsu *et al*., 2019). Modern breeding techniques, including genetic modification and marker-assisted selection, offer promising solutions to improve yield and disease resistance.However, the adoption of these technologies comes with ethical, environmental, and regulatory concerns (Saheed *et al.,* 2021). There is a need for a balanced approach that integrates scientific advancements with sustainable farming practices to enhance cocoa production while preserving biodiversity and farmer livelihoods. Future research should focus on refining genetic modification techniques to ensure consumer acceptance, improving disease-resistant cocoa strains, and enhancing soil conservation methods. By combining traditional knowledge with technological innovation, the cocoa industry can achieve long-term sustainability and productivity, securing its role in global agriculture and health.

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