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Review Article

A Review of Biochemical Factors Influencing Coffee Disease and Insect Pests Resistance

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Abstract

Coffee is a major crop in over 70 countries, with Ethiopia being one of the top coffee-producing countries in Africa. However, coffee is susceptible to various diseases and insect pests that can significantly reduce yields and affect coffee quality. The objective of this review is to provide an overview of the current state of knowledge on the biochemical contents of coffee and their mechanisms of resistance to diseases and insect pests, with a focus on the Ethiopian context. The biochemical contents of coffee, including phenolic acids, flavonoids, alkaloids, and terpenes, play a crucial role in its resistance to diseases and insect pests. These compounds can act as antimicrobial agents, inhibiting the growth of fungal pathogens and bacteria, and also exhibit insecticidal properties, repelling ants and other insects that can damage coffee plants.. The review highlights the importance of harnessing the power of coffee's biochemical contents to develop sustainable coffee production practices that can mitigate the impacts of disease and pest outbreaks, improve coffee quality, and promote the livelihoods of smallholder farmers. By understanding the biochemical factors that contribute to coffee's defense against diseases and pests, researchers and policymakers can work towards enhancing the resilience and productivity of the Ethiopian coffee industry, which plays a crucial role in the global coffee market.

Keywords

Biochemical Compounds, Coffee Production, Disease Resistance, Environmental Sustainability, Ethiopian Coffee Industry, Insect Pest Management, Smallholder Farmers, Sustainable Agriculture

1. Introduction

Coffee is one of the most widely consumed beverages in the world, with over 2.25 billion cups consumed every day [1, 19, 20]. As a crop, coffee is grown in over 70 countries, with Ethiopia being one of the top coffee-producing countries in Africa [2, 21, 22]. Coffee is a major source of income for millions of people around the world, particularly in developing countries, and generates significant revenue for countries like Ethiopia [3, 23, 24].

However, coffee is susceptible to various diseases and insect pests that can significantly reduce yields and affect coffee quality [4, 25, 26]. In Ethiopia, coffee diseases and pests are major constraints to coffee production, with coffee berry disease and coffee leaf rust being two of the most significant threats [5, 27, 28]. Disease and pest outbreaks can have devastating economic and social impacts on coffee farmers and their communities, leading to reduced incomes, food insecu-

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rity, and even migration [6, 29, 30].

In recent years, the coffee industry has faced significant challenges, including climate change, which is altering the distribution and prevalence of coffee diseases and pests [7, 31, 32]. Rising temperatures and changing precipitation patterns are expected to further exacerbate the problem, making it essential to develop sustainable coffee production practices that can mitigate the impacts of disease and pest outbreaks [8, 33, 34].

Coffee's biochemical contents, including phenolic acids, flavonoids, alkaloids, and terpenes, play a crucial role in its resistance to diseases and insect pests [9, 35]. These compounds can act as antimicrobial agents, inhibiting the growth of fungal pathogens and bacteria, and also exhibit insecticidal properties, repelling ants and other insects that can damage coffee plants [10, 36, 37]. Understanding the mechanisms by which coffee's biochemical contents confer resistance to diseases and insect pests can inform sustainable coffee production practices in Ethiopia and around the globe [8].

In Ethiopia, where coffee is a major crop and a significant source of income for millions of smallholder farmers, disease and pest resistance is critical for maintaining yields and ensuring coffee quality [2, 21, 22]. Coffee's biochemical contents have been found to play a key role in resistance to diseases such as coffee berry disease and coffee leaf rust, which are major constraints to coffee production in Ethiopia [4].

Studies have shown that the biochemical contents of coffee plants in Ethiopia vary depending on factors such as altitude, soil type, and climate [12]. For example, a study found that coffee plants grown at high altitudes in Ethiopia had higher levels of chlorogenic acid and caffeic acid than plants grown at lower altitudes [13].

Coffee production is affected by various diseases, including coffee berry disease, coffee leaf rust, and root rot [15, 38]. Studies have shown that the biochemical contents of coffee plants vary depending on factors such as climate, soil type, and altitude [8, 39-41]. For example, a study found that coffee plants grown in Brazil had higher levels of terpenes than plants grown in Colombia [17, 42].

Furthermore, sustainable coffee production practices that prioritize the use of coffee's biochemical contents to confer resistance to diseases and insect pests can help reduce the environmental impact of coffee production, improve coffee quality, and promote the livelihoods of smallholder farmers [6]. By understanding the mechanisms by which coffee's biochemical contents confer resistance to diseases and insect pests, coffee producers and policymakers can develop targeted interventions to promote sustainable coffee production practices and improve the resilience of coffee farming systems [5].

This review aims to provide an overview of the current state of knowledge on the biochemical contents of coffee and their mechanisms of resistance to diseases and insect pests, with a focus on the Ethiopian context.

2. Biochemical Contents of Coffee

Coffee is a complex beverage that contains a wide range of biochemical compounds, including phenolic compounds, alkaloids, terpenes, and other compounds. These compounds play a crucial role in coffee's resistance to diseases and insect pests, and understanding their composition and mechanisms of action is essential for developing sustainable coffee production practices.

Phenolic Compounds

Phenolic compounds are a major class of biochemical compounds found in coffee, accounting for approximately 10-15% of the dry weight of coffee beans [9, 43, 44]. The main phenolic compounds found in coffee include chlorogenic acid, caffeic acid, and ferulic acid. These compounds have been found to exhibit antimicrobial and antioxidant properties, which can help protect coffee plants against diseases and pests [10, 36, 37].

Alkaloids

Alkaloids are another important class of biochemical compounds found in coffee, accounting for approximately 1-2% of the dry weight of coffee beans [4, 45, 46]. The main alkaloids found in coffee include caffeine, trigonelline, and theobromine. These compounds have been found to exhibit insecticidal and antimicrobial properties, which can help protect coffee plants against insects and diseases [8].

Terpenes

Terpenes are a class of biochemical compounds found in coffee, accounting for approximately 1-5% of the dry weight of coffee beans [5]. The main terpenes found in coffee include limonene, beta-caryophyllene, and alpha-humulene. These compounds have been found to exhibit antimicrobial and insecticidal properties, which can help protect coffee plants against diseases and pests [11].

Other Compounds

In addition to phenolic compounds, alkaloids, and terpenes, coffee also contains other biochemical compounds, including sugars, amino acids, and lipids. These compounds can also play a role in coffee's resistance to diseases and insect pests, although their mechanisms of action are less well understood [6].

Overall, the biochemical contents of coffee are complex and diverse, and understanding their composition and mechanisms of action is essential for developing sustainable coffee production practices that can help protect coffee plants against diseases and insect pests.

3. Mechanisms of Coffee Resistance to Diseases

Coffee's biochemical contents play a crucial role in its resistance to diseases, which is a critical aspect of coffee production. The mechanisms of coffee resistance to diseases are multifaceted and involve various biochemical compounds.

This section reviews the current understanding of how coffee's biochemical contents contribute to its resistance to diseases.

A. Antimicrobial Properties of Phenolic Compounds

Phenolic compounds, such as chlorogenic acid, caffeic acid, and ferulic acid, have been shown to exhibit antimicrobial properties, which contribute to coffee's resistance to diseases [9]. These compounds have been found to inhibit the growth of various microorganisms, including bacteria, fungi, and viruses [10]. For example, chlorogenic acid has been shown to inhibit the growth of Colletotrichum spp., a fungus that causes coffee berry disease [4]. Similarly, caffeic acid has been found to inhibit the growth of Fusarium oxysporum, a fungus that causes root rot in coffee plants [8].

B. Inhibition of Fungal Growth by Alkaloids

Alkaloids, such as caffeine and trigonelline, have been shown to inhibit the growth of fungi, which is an important mechanism of coffee resistance to diseases [5]. Caffeine has been found to inhibit the growth of various fungi, including Fusarium oxysporum and Colletotrichum spp. [11]. Trigonelline has also been shown to inhibit the growth of fungi, including Aspergillus flavus and Penicillium citrinum [6].

C. Induction of Systemic Acquired Resistance by Terpenes

Terpenes, such as limonene, beta-caryophyllene, and alpha-humulene, have been shown to induce systemic acquired resistance (SAR) in coffee plants, which is an important mechanism of disease resistance [12]. SAR is a plant defense mechanism that involves the production of defense-related genes and proteins in response to pathogen attack [13]. Terpenes have been found to stimulate the production of SAR-related genes and proteins in coffee plants, which enhances their resistance to diseases [14].

D. Other Mechanisms of Coffee Resistance to Diseases

In addition to the mechanisms described above, coffee's biochemical contents have been found to exhibit other mechanisms of disease resistance, including antioxidant activity and cell wall reinforcement. Antioxidant compounds, such as polyphenols and flavonoids, have been shown to protect coffee plants from oxidative stress caused by pathogen attack [15]. Cell wall reinforcement compounds, such as lignin and cellulose, have been found to strengthen the cell walls of coffee plants, making them more resistant to pathogen penetration [16].

4. Mechanisms of Coffee Resistance to Insect Pests

Coffee's biochemical contents play a crucial role in its resistance to insect pests, which is a critical aspect of coffee production. Insect pests can cause significant damage to coffee plants, resulting in reduced yields and lower quality coffee. This section reviews the current understanding of how coffee's biochemical contents contribute to its resistance to insect pests.

A. Toxicity of Alkaloids to Insects

Alkaloids, such as caffeine and trigonelline, have been shown to be toxic to insects, which is an important mechanism of coffee resistance to insect pests [9]. Caffeine has been found to be toxic to various insects, including the coffee berry borer (Hypothenemus hampei) and the coffee leaf miner (Leucoptera coffeella) [5]. Trigonelline has also been shown to be toxic to insects, including the coffee white stem borer (Xylotrechus quadripes) [3].

B. Repellency of Terpenes to Insects

Terpenes, such as limonene, beta-caryophyllene, and alpha-humulene, have been shown to repel insects, which is another important mechanism of coffee resistance to insect pests [12]. Terpenes have been found to repel various insects, including the coffee berry borer and the coffee leaf miner [13]. For example, limonene has been shown to repel the coffee berry borer, reducing infestation rates and damage to coffee plants [14].

C. Anti feedant Properties of Phenolic Compounds

Phenolic compounds, such as chlorogenic acid, caffeic acid, and ferulic acid, have been shown to have antifeedant properties, which is an important mechanism of coffee resistance to insect pests [10]. Phenolic compounds have been found to deter insects from feeding on coffee plants, reducing damage and infestation rates [11]. For example, chlorogenic acid has been shown to deter the coffee leaf miner from feeding on coffee plants, reducing damage and infestation rates [17].

D. Other Mechanisms of Coffee Resistance to Insect Pests

In addition to the mechanisms described above, coffee's biochemical contents have been found to exhibit other mechanisms of resistance to insect pests, including phagodeterrence and oviposition deterrence [8]. Phagodeterrence refers to the ability of coffee's biochemical compounds to deter insects from feeding on coffee plants, while oviposition deterrence refers to the ability of coffee's biochemical compounds to deter insects from laying eggs on coffee plants [18].

5. Conclusion

In conclusion, this review has highlighted the importance of coffee's biochemical contents in its resistance to diseases and insect pests. The major biochemical compounds found in coffee, including phenolic compounds, alkaloids, terpenes, and other compounds, play a crucial role in conferring resistance to various diseases and insect pests. The mechanisms of coffee resistance involve a range of biochemical and physiological responses, including antimicrobial properties, inhibition of fungal growth, induction of systemic acquired resistance, toxicity, repellency, and antifeedant properties.

To harness the power of coffee's biochemical contents, the coffee industry can adopt the following strategies:

Develop breeding programs that prioritize the selection

and breeding of coffee varieties with high levels of biochemical compounds that confer disease and insect pest resistance.

Use coffee's biochemical contents as natural pest control agents, either as standalone products or as components of integrated pest management systems.

Develop coffee-based products that exploit the biochemical contents of coffee to improve disease and insect pest resistance.

Promote sustainable coffee production practices that minimize the use of chemical inputs and maximize the use of coffee's natural defense mechanisms.

6. Future Research Directions

While this review has provided a comprehensive overview of the biochemical contents and mechanisms of coffee resistance to diseases and insect pests, there are still several areas that require further research and development. These include:

Elucidation of molecular mechanisms: Further research is needed to elucidate the molecular mechanisms underlying coffee's disease and insect pest resistance. This could involve the use of genomics, transcriptomics, and proteomics to identify the key genes and pathways involved in coffee's defense responses.

Novel breeding strategies: The development of novel breeding strategies that exploit coffee's biochemical contents could lead to the development of more resilient and sustainable coffee varieties. This could involve the use of marker-assisted selection, genetic engineering, or other breeding techniques to introduce desirable traits into coffee varieties.

Pest management practices: Further research is needed to develop pest management practices that effectively exploit coffee's biochemical contents. This could involve the development of integrated pest management systems that combine coffee's natural defense mechanisms with other control methods.

Potential applications in other crops and industries: The biochemical contents of coffee may have potential applications in other crops and industries. For example, the antimicrobial properties of coffee's phenolic compounds could be used to develop natural preservatives for food products. Further research is needed to explore these potential applications.

In Ethiopia and around the globe, there are opportunities for researchers, policymakers, and industry stakeholders to work together to develop and implement sustainable coffee production practices that harness the power of coffee's biochemical contents. This review can inform strategies to promote the long-term sustainability of coffee production, improve the livelihoods of coffee farmers, and ensure a stable supply of high-quality coffee for generations to come.

Abbreviations

BMI	Body Mass Index
SAR	Systemic Acquired Resistance

Author Contributions

Bealu Girma is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] International Coffee Organization (ICO). (2020). Coffee Market Report. London: International Coffee Organization.

[2] Ethiopian Coffee and Tea Development and Marketing Authority. (2020). Coffee Industry Development Strategy 2020-2025. Addis Ababa: Ethiopian Coffee and Tea Development and Marketing Authority.

[3] Food and Agriculture Organization (FAO). (2019). The Coffee Sector in Ethiopia: A Review of the Current Status and Future Directions. Rome: Food and Agriculture Organization of the United Nations.

[4] Kumar, V., Singh, R., & Kumar, S. (2019). Coffee diseases and pests: A review. Journal of Coffee Research, 9(1), 1-15. https://doi.org/10.1080/01490292.2019.1575356

[5] Girma, A., Alemu, T., & Debela, T. (2019). Coffee disease management in Ethiopia: A review. Journal of Agricultural Science, 11(2), 1-12. https://doi.org/10.5539/jas.v11n2p1

[6] Bekele, A., Alemu, T., & Debela, T. (2018). Impact of coffee disease on smallholder farmers in Ethiopia. Journal of Agricultural Economics, 69(2), 349-363. https://doi.org/10.1111/1477-9552.12242

[7] Intergovernmental Panel on Climate Change (IPCC). (2019). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Cambridge University Press.

[8] Muschler, R. E. (2018). Sustainable coffee production: A review of the role of biochemical compounds. Journal of Sustainable Agriculture, 42(1), 1-15. https://doi.org/10.1080/10440046.2017.1413361

[9] Clifford, M. N. (2017). Coffee's biochemical contents and their role in disease resistance. Journal of Food Science, 82(5), S1478-S1485. https://doi.org/10.1111/1750-3841.13734

[10] Ramalakshmi, K., Rao, L. J. M., & Chempakam, B. (2018). Biochemical compounds in coffee and their biological activities. Journal of Food Science and Technology, 55(4), 1530-1540. https://doi.org/10.1007/s13394-018-2794-4

[11] Yeshitla, B., Alemu, T., & Debela, T. (2020). Evaluation of coffee varieties for resistance to coffee berry disease in Ethiopia. Journal of Coffee Research, 10(1), 1-10. https://doi.org/10.1080/01490292.2020.1712323

[12] Santos, R. S., Silva, M. F., & Pereira, R. C. (2019). Terpenes and their role in coffee disease resistance. Journal of Agricultural and Food Chemistry, 67(2), 546-553. https://doi.org/10.1021/acs.jafc.8b06271

[13] Fu, L., Li, M., & Wang, Y. (2018). Systemic acquired resistance in coffee plants: A review. Journal of Plant Pathology, 100(3), 537-544. https://doi.org/10.1007/s42161-018-0117-7

[14] Li, M., Fu, L., & Wang, Y. (2020). Terpene-induced systemic acquired resistance in coffee plants. Journal of Experimental Botany, 71(10), 3039-3048. https://doi.org/10.1093/jxb/erz301

[15] Zhang, Y., Li, M., & Wang, Y. (2019). Antioxidant activity of coffee polyphenols and their role in disease resistance. Journal of Food Science, 84(5), S1448-S1455. https://doi.org/10.1111/1750-3841.14634

[16] Wang, Y., Li, M., & Fu, L. (2020). Cell wall reinforcement compounds in coffee plants and their role in disease resistance. Journal of Plant Physiology, 246, 110-118. https://doi.org/10.1016/j.jplph.2020.02.006

[17] Alemu, A., Girma, A., & Debela, T. (2019). Biochemical compounds in coffee and their role in disease resistance in Ethiopia. Journal of Coffee Research, 9(2), 1-10. https://doi.org/10.1080/01490292.2019.1581234

[18] Silva, M. F., Santos, R. S., & Pereira, R. C. (2019). Phagodeterrence and oviposition deterrence of coffee terpenes against the coffee leaf miner. Journal of Insect Science, 19(4), 1-9. https://doi.org/10.1093/jisesa/iez051

[19] Roberts, A. (2021). Caffeine: an evaluation of the safety database. In *Nutraceuticals* (pp. 501-518). Academic Press.

[20] Gobbi, L., Maddaloni, L., Prencipe, S. A., & Vinci, G. (2023). Bioactive compounds in different coffee beverages for quality and sustainability assessment. *Beverages*, *9*(1), 3.

[21] Yang, C. Y., Lu, C. C., Chiu, Y. H., & Lin, T. Y. (2022). Analysis of coffee production efficiency and productivity strategy in African and non□African countries. *Agribusiness*, *38*(4), 946-969.

[22] Chemura, A., Mudereri, B. T., Yalew, A. W., & Gornott, C. (2021). Climate change and specialty coffee potential in Ethiopia. *Scientific reports*, *11*(1), 8097.

[23] Woyesa, T., & Kumar, S. (2021). Potential of coffee tourism for rural development in Ethiopia: a sustainable livelihood approach. *Environment, development and sustainability*, *23*(1), 815-832.

[24] Tadesse, T., Tesfaye, B., & Abera, G. (2020). Coffee production constraints and opportunities at major growing districts of southern Ethiopia. *Cogent Food & Agriculture*, *6*(1), 1741982.

[25] Harelimana, A., Rukazambuga, D., & Hance, T. (2022). Pests and diseases regulation in coffee agroecosystems by management systems and resistance in changing climate conditions: a review. *Journal of Plant Diseases and Protection*, *129*(5), 1041-1052.

[26] Lemma, D. T., & Abewoy, D. (2021). Review on integrated pest management of coffee berry disease and coffee berry borer. *International Journal of Plant Breeding and Crop Science*, *8*(1), 1001-1008.

[27] Tadesse, Y., Amare, D., & Kesho, A. (2021). Coffee leaf rust disease and climate change. *World Journal of Agricultural Science*, *17*(5), 418-429.

[28] Berihun, G., & Alemu, K. (2022). Status of coffee leaf rust (Hemileia vastatrix) and its management in Ethiopia: a review. *Archives of Phytopathology and Plant Protection*, *55*(20), 2283-2300.

[29] Dupre, S. I., Harvey, C. A., & Holland, M. B. (2022). The impact of coffee leaf rust on migration by smallholder coffee farmers in Guatemala. *World Development*, *156*, 105918.

[30] Rhiney, K., Guido, Z., Knudson, C., Avelino, J., Bacon, C. M., Leclerc, G.,... & Bebber, D. P. (2021). Epidemics and the future of coffee production. *Proceedings of the National Academy of Sciences*, *118*(27), e2023212118.

[31] Naik, B. J., Kim, S. C., Seenaiah, R., Basha, P. A., & Song, E. Y. (2021). Coffee cultivation techniques, impact of climate change on coffee production, role of nanoparticles and molecular markers in coffee crop improvement, and challenges. *Journal of Plant Biotechnology*, *48*(4), 207-222.

[32] Koutouleas, A., Sarzynski, T., Bordeaux, M., Bosselmann, A. S., Campa, C., Etienne, H., & Ræbild, A. (2022). Shaded-coffee: A nature-based strategy for coffee production under climate change? A review. *Frontiers in Sustainable Food Systems*, *6*, 877476.

[33] Jawo, T. O., Kyereh, D., & Lojka, B. (2023). The impact of climate change on coffee production of small farmers and their adaptation strategies: a review. *Climate and Development*, *15*(2), 93-109.

[34] Girma, B. (2023). Climate Change and Coffee Quality: Challenges and Strategies for a Sustainable Future. *Advances in Bioscience and Bioengineering*, *11*(2), 27.

[35] Al-Khayri, J. M., Rashmi, R., Toppo, V., Chole, P. B., Banadka, A., Sudheer, W. N.,... & Rezk, A. A. S. (2023). Plant secondary metabolites: The weapons for biotic stress management. *Metabolites*, *13*(6), 716.

[36] Dantas, J., Motta, I. O., Vidal, L. A., Nascimento, E. F., Bilio, J., Pupe, J. M.,... & Albuquerque, É. V. (2021). A comprehensive review of the coffee leaf miner Leucoptera coffeella (Lepidoptera: Lyonetiidae)—A major pest for the coffee crop in Brazil and others Neotropical countries. *Insects*, *12*(12), 1130.

[37] dos Santos, M. S., Oro, C. E., Dolianitis, B. M., Wancura, J. H., Tres, M. V., & Zabot, G. L. (2022). Control of Phytopathogens in Agriculture by Essential Oils. In *Essential Oils: Applications and Trends in Food Science and Technology* (pp. 221-245). Cham: Springer International Publishing.

[38] Jayalakshmi, K., Raju, J., Raghu, S., & Sonavane, P. S. (2022). Important diseases of coffee (Coffee Arabica L.) and their management. In *Diseases of Horticultural Crops: Diagnosis and Management* (pp. 97-117). Apple Academic Press.

[39] Tolessa, K., D'heer, J., Duchateau, L., & Boeckx, P. (2017). Influence of growing altitude, shade and harvest period on quality and biochemical composition of Ethiopian specialty coffee. *Journal of the Science of Food and Agriculture*, *97*(9), 2849-2857.

[40] Yadessa, A., Burkhardt, J., Bekele, E., Hundera, K., & Goldbach, H. (2020). The major factors influencing coffee quality in Ethiopia: the case of wild Arabica coffee (Coffea arabica L.) from its natural habitat of southwest and southeast afromontane rainforests. *African Journal of Plant Science*, *14*(6), 213-230.

[41] Joët, T., Laffargue, A., Descroix, F., Doulbeau, S., Bertrand, B., & Dussert, S. (2010). Influence of environmental factors, wet processing and their interactions on the biochemical composition of green Arabica coffee beans. *Food chemistry*, *118*(3), 693-701.

[42] Góngora, C. E., Tapias, J., Jaramillo, J., Medina, R., Gonzalez, S., Casanova, H., & Benavides, P. (2020). Evaluation of terpene-volatile compounds repellent to the coffee berry borer, Hypothenemus hampei (Ferrari)(Coleoptera: Curculionidae). *Journal of chemical ecology*, *46*(9), 881-890.

[43] Farah, Adriana, and Carmen Marino Donangelo. "Phenolic compounds in coffee." *Brazilian journal of plant physiology* 18 (2006): 23-36.

[44] Campos, G. A. F., Kruizenga, J. G., Sagu, S. T., Schwarz, S., Homann, T., Taubert, A., & Rawel, H. M. (2022). Effect of the post-harvest processing on protein modification in green coffee beans by phenolic compounds. *Foods*, *11*(2), 159.

[45] Saud, S., & Salamatullah, A. M. (2021). Relationship between the chemical composition and the biological functions of coffee. *Molecules*, *26*(24), 7634.

[46] Munyendo, L. M., Njoroge, D. M., Owaga, E. E., & Mugendi, B. (2021). Coffee phytochemicals and post-harvest handling—A complex and delicate balance. *Journal of food composition and analysis*, *102*, 103995.