The Impact of Self-Induced Anaerobic Fermentation (SIAF) on Coffee Antioxidants: A Review

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Abstract

Coffee is one of the most traded commodities in the world and plays a crucial role in Indonesia's economy. The price of coffee is intricately tied to its quality and perceived health benefits. Recently, there has been a growing interest in studying the effect of post-harvest processing, particularly fermentation, on coffee antioxidants. Among the various fermentation techniques, self-induced anaerobic fermentation (SIAF) has emerged as an innovative approach to enhance coffee antioxidants. Despite its potential, the effects of SIAF on coffee antioxidants appear to be inconsistent, and the underlying mechanisms remain unclear. This review aims to evaluate the potential impacts of SIAF on coffee's antioxidant contents and activities. Relevant articles from 2013 to 2023 that discuss the effects of SIAF on coffee antioxidants were reviewed. The results indicate that SIAF may enhance coffee's antioxidant contents and activities, but the effects appear to depend on the microorganisms involved in the fermentation process. The effects may be linked to the microbial activities and enzymatic processes that change the biochemical compositions of the coffee during fermentation. Knowledge of the mechanisms underlying the effects is important for optimal integration of SIAF into the coffee industry. This study contributes valuable insights into the promising role of SIAF in enhancing coffee antioxidants and emphasizes the importance of continued research in this field.

Keywords: Antioxidant, Anaerobic Fermentation, Coffee, Microbes, Polyphenol.

INTRODUCTION

Coffee is a popular beverage brewed from roasted coffee beans cultivated in more than 70 countries. It serves a significant role in the Indonesian economy as a valued commodity [1,2]. Coffee is highly esteemed for its sensory attributes and psychotropic characteristics. Coffee brew possesses sensory qualities and provides a source of antioxidants, such as chlorogenic acids, caffeine, and other substances that can potentially provide health benefits [3].

The post-harvest processing of coffee is an essential part of coffee production that substantially impacts coffee qualities and functional characteristics [4]. Coffee's functional qualities, especially its antioxidants, are greatly influenced by its post-harvest processing. One of the vital stages of post-harvest processing is the fermenting stage. Self-induced anaerobic fermentation (SIAF) has become a viable method for coffee processing among the numerous fermentation techniques. SIAF gradually generates CO_2 through microbial metabolism, resulting in an oxygen-deficient setting that improves the fermentative abilities of lactic acid bacteria (LAB) and yeasts [5]. This method has been found to positively impact the quality of coffee, making it crucial to understand its specific impacts on the antioxidant content of coffee beans [6].

The impact of fermentation on the antioxidant characteristics of coffee is an important factor in coffee production. The antioxidants in coffee play an important role in the functional qualities of coffee, contributing to the health-promoting advantages of coffee as well as its sensory attributes. The fermentation process involving lactic acid bacteria enhances the quality characteristics and antioxidant activities of espresso coffee. The highest sensory scores are achieved with 30% (w/v) green bean fermentation [7]. Other research also observed improved antioxidant properties, increased total phenol and flavonoid content, and reduced tannin content in medium and dark-roasted coffee when green coffee beans were fermented with *Wickerhamomyces anomalus* yeast [8]. Given the various results and methods employed in coffee fermentation, a comprehensive understanding of the impact of SIAF on the antioxidant content is crucial. This knowledge is essential for optimizing the fermentation process and ensuring the production of high-quality coffee products.

Despite the conventional wet fermentation method commonly used in coffee processing, SIAF presents an innovative strategy that has shown the ability to improve the quality of coffee [9,10]. Nevertheless, the effect of SIAF on coffee's antioxidant contents and activities appears inconsistent, and the underlying mechanisms remain unclear. Therefore, there is a

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gap in the research regarding the influence of SIAF on the antioxidant characteristics of coffee, underscoring the necessity for additional exploration in this area.

The primary aim of this study is to assess the precise impact of SIAF on the antioxidants in coffee beans. This research intends to provide valuable insights into the impact of SIAF on the functional qualities of coffee by thoroughly analyzing the changes in polyphenolic extracts and the antioxidant capacity of coffee beans. Furthermore, this study aims to investigate the relationship between the distinct microbial populations linked to SIAF and the production of antioxidants in coffee beans, thereby improving the understanding of this innovative fermentation technique.

METHOD

The selection process involved identifying the most pertinent articles in the field of coffee by-products spanning from 2013 to 2023. This search was conducted across reputable databases such as Elsevier, Web of Science, and Pubmed. The keywords employed in the data search encompassed terms like coffee, green bean, roasted bean, post-harvest processing, self-induced anaerobic fermentation, microbes in anaerobic fermentation, lactic acid bacteria, phenolic, chlorogenic acids, and antioxidant. Additionally, references predating 2013 were incorporated to elucidate foundational concepts. This paper benefited from the insights gathered from analyzing approximately 40 articles.

RESULT AND DISCUSSION

Coffee Fermentation

Fermentation is an important technique in food processing, involving the active role of microorganisms, especially LAB. In fermentation, LAB plays a role in breaking down the sugar contained in food into simpler components, such as alcohol and amino acids [11]. Fermentation has various applications in the food industry, including in coffee processing, to improve the quality and flavor of coffee [2].

The fermentation process can be carried out using two main methods: anaerobic fermentation and aerobic fermentation. Anaerobic fermentation, which does not require the presence of oxygen in the process, is generally easier to perform. Anaerobic fermentation methods include various approaches, including conventional fermentation, adding LAB cultures, and utilizing fruit peels as a substrate for microorganisms [12]. The time required in the fermentation process varies, depending on the type of microorganism used. For example, LAB requires a long time to degrade sugar in coffee into simpler amino acids.

Fermentation plays an essential role in changing the chemical composition of coffee beans, which contributes to the development of desirable sensory characteristics. The interaction between microorganisms and coffee compounds during fermentation produces a variety of flavor compounds, including caramel and fruit aromas [13]. This transformation is influenced by the metabolic activity of the fermenting microorganisms, such as yeasts and lactic acid bacteria, which produce organic acids, alcohols, and other volatile compounds [14]. These compounds contribute to the overall aroma and flavor complexity of fermented coffee.

Self-Induced Anaerobic Fermentation (SIAF) in Coffee Processing

SIAF is an innovative technique that has attracted interest in the coffee sector due to its ability to improve coffee quality and flavor attributes. This process entails the gradual production of carbon dioxide (CO_2) through microbial metabolism, resulting in an oxygen-deficient environment that enhances the fermentative process performed by LAB and yeasts. SIAF has been discovered to enhance the synthesis of desirable chemicals, including lactic acid, esters, aldehydes, and ketones, which can have a beneficial impact on the taste and fragrance of coffee. The technique has demonstrated a notable enhancement in the ultimate beverage, rendering it a promising strategy for coffee production [5,9].

The comparison between the conventional post-harvest process of coffee and SIAF is that SIAF has been discovered to consist of significantly distinct dominant microbial groups in contrast to standard coffee processing (Fig. 1). The distinctive composition of microorganisms in this community might result in specific alterations in various layers of coffee beans, ultimately influencing the taste and excellence of the end product. Moreover, SIAF has demonstrated the ability to improve the fermentation capabilities of LAB and yeasts, producing specific metabolites that contribute to the desirable sensory characteristics of coffee. The differences between SIAF and conventional fermentation techniques distinguish it and emphasize its ability to improve the quality of coffee [9].

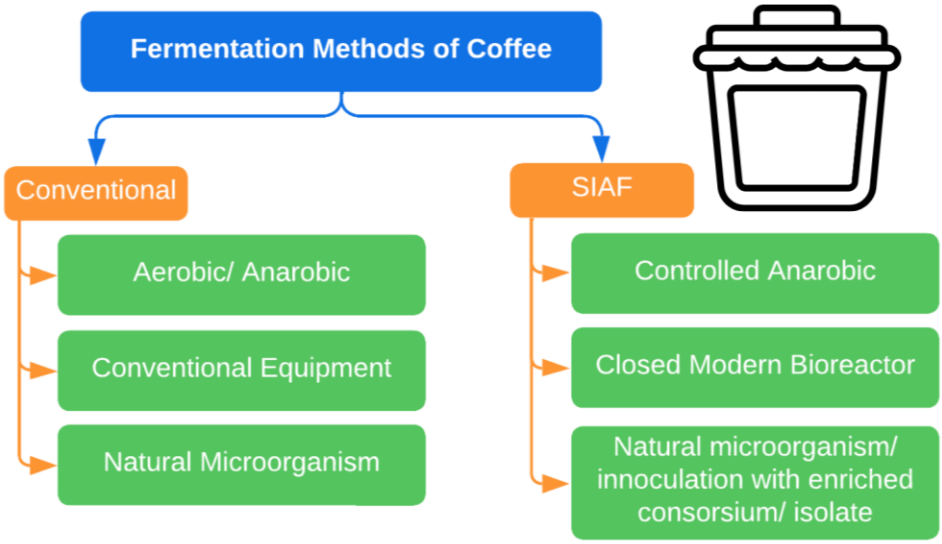

Figure 1. The Conventional Process of Coffee Post-Harvest and Self-Induced Anaerobic Fermentation (SIAF)

The influence of SIAF on flavor and quality is multifaceted, determined by the particular composition of coffee beans, the microbial community participating in the fermentation process, and the fermentation conditions. Research has shown that SIAF can lead to noticeable changes in the chemical component of coffee beans, which ultimately impact the overall sensory profile and quality of the beverage [10, 15]. In addition, the unique microbial succession and metabolic activities associated with SIAF may influence coffee chemical compositions and sensory characteristics, making it a distinctive and exciting approach to improving coffee quality [10].

SIAF in coffee processing has numerous advantages compared to conventional fermentation processes, resulting in improved coffee quality and flavor attributes. Studies have demonstrated that the SIAF method can significantly enhance the quality of coffee produced on farms lacking proper facilities, making it relevant for small-scale coffee farmers. SIAF has been found to enhance the quality of coffee, with wet fermentation of *Coffea canephora* using the SIAF method leading to improved coffee quality [10]. The distinct composition and functional characteristics of the microbial population in SIAF can benefit the taste and scent of coffee, ultimately leading to an improvement in coffee quality [5]. SIAF enhances the fermentative ability of LAB and yeasts, synthesizing particular metabolites that contribute to the desired sensory characteristics of coffee. The enhanced fermentative capacity might lead to the synthesis of specific substances, such as lactic acid, esters, aldehydes, and ketones, which favorably impact the taste and scent of coffee [10,15].

In addition, SIAF has been demonstrated to impact the microbial composition of anaerobic-fermented coffee, potentially suppressing microbes that produce ochratoxin and reducing the health hazards associated with coffee consumption [16]. This feature of SIAF provides the potential to improve the production of coffee by ensuring its safety and quality. The presence of SIAF has been seen to have a meaningful impact on coffee beans' antioxidant content and activity, resulting in modifications in the polyphenolic extracts and antioxidant capacity [9]. It can facilitate the production of coffee with augmented health advantages and enhanced overall quality.

SIAF is an up-and-coming innovation in coffee processing that provides numerous benefits compared to conventional fermentation methods. This novel approach not only improves the overall quality and fermentation performance of coffee but also substantially impacts the diversity of microorganisms, ultimately affecting the antioxidant content of the end product. The microorganisms' unique composition and corresponding metabolic processes in SIAF sets it apart from conventional fermentation techniques. To optimize the capabilities, conducting additional studies and implementing SIAF widely in coffee processing is crucial. It will ensure a thorough understanding of its effects and the most effective integration into the industry.

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Antioxidants in Coffee

Coffee is widely recognized as an abundant source of antioxidants. Its antioxidant activity is attributed to a variety of compounds, including phenolics, flavonoids, tannins, chlorogenic, ferulic, and caffeic acids, as well as melanoidins [3,17,18]. Antioxidants are essential for maintaining good health and avoiding diseases by counteracting oxidative stress within the body. Extensive research has been conducted to comprehend the impact of antioxidants in coffee on human health, focusing on their various forms and roles.

Antioxidants in Coffee: Types and Roles

Coffee has been recognized as a substantial source of antioxidants, including the bean, husks, pulp, and silverskin. The components mentioned several antioxidant compounds, e.g. phenolics and flavonoids, which can be extracted using aqueous, methanolic, and ethanolic extraction [17]. Moreover, the antioxidant properties of coffee are attributed to specific components such as chlorogenic, ferulic, and caffeic acids, along with melanoidins produced during the roasting process [3,18]. Antioxidants are crucial in eliminating harmful free radicals and minimizing oxidative harm within the body, thereby contributing to the potential health advantages of consuming coffee.

Green and roasted coffees exhibit different bioactivity and health characteristics. Green coffee demonstrates superior antioxidant capacity and influences gut microbiota composition after fermentation [19]. Green coffee beans are abundant in polyphenolic antioxidants, including chlorogenic, caffeic, ferulic, and n-coumaric acids. Melanoidins, which are dark pigments, are formed during the roasting process of coffee and possess potent antioxidant properties. Caffeine and trigonelline are recognized as antioxidants in coffee. The presence of chlorogenic, ferulic, caffeic, and n-coumaric acids in coffee contributes to its antioxidant action [18].

The Impact of Coffee Antioxidants on Health.

Coffee is a rich source of beneficial antioxidants, with multiple components contributing to its antioxidant action. Antioxidants are vital in enhancing well-being and averting illnesses by counteracting oxidative stress within the body. The drinking of coffee has been linked to several health advantages, such as a lower risk of getting type 2 diabetes, liver ailments, gallstones, and some forms of cancer [20]. In addition, caffeine promoted apoptosis, elevated p53 levels in keratinocytes, and inhibited DNA damage caused by UVB irradiation. The components of coffee have the ability to defend against the harmful effects of sunlight, such as premature aging of the skin and the development of skin cancer [21].

The antioxidant activity of coffee is believed to contribute to these health benefits through various mechanisms, including scavenging free radicals, donating hydrogen and electrons, and reducing oxidative stress in the body [22]. The coffee's antioxidant activities are due to many chemicals, e.g. chlorogenic acid, caffeic acid, and melanoidins, which are produced during the roasting procedure [18]. The wide array of antioxidants in coffee, originating from green and roasted beans, contribute to its elevated antioxidant capacity and potential health advantages. Consuming the proper amount of coffee might offer several health advantages. However, excessive consumption of caffeine can lead to symptoms such as restlessness, unease, and sleeplessness and may not be appropriate for persons with poor blood pressure regulation.

Anaerobic Fermentation on Antioxidant Content

The impact of SIAF coffee on the antioxidant content of coffee beans has been a topic of recent research. SIAF resulted in different dominant microbial communities than conventional coffee processing, suggesting that SIAF affect coffee antioxidant qualities [9]. The microbial activity promoted by SIAF leads to modifications in the polyphenolic extracts and antioxidant capacity. An increase in antioxidant activity has been associated with the production of phenolic compounds and other bioactive substances during the SIAF process [15]. Several studies that have investigated the effects of SIAF on the antioxidant content of coffee are shown in Table 1.

The Liberica variation exhibits a significant increase in antioxidant activity, as demonstrated by an IC_{50} of 27.27 ppm, while the addition of Liberica cherry extract causes a decrease in caffeine levels to 0.12% [27]. In Brazil Ipanema coffee, fermentation with *Saccharomyces* sp. decreased moisture levels and upswing the total phenol content [28]. When subjected to a microbial cocktail of lactic acid bacteria and yeast, Robusta coffee exhibits an impressive surge in total phenol content to 383.24 mg GAE 100 g^{-1} and a corresponding 170.71% increase in antioxidant activity [29].

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Table 1. Several Studies of SIAF Effect

Coffee Species	Starter	Results
Robusta [23]	*Bacillus subtilis* and *Saccharomyces cerevisiae* in sugarcane and banana juice	- The antioxidant activity, total polyphenol content, and total flavonoid content increased. - Fermented coffee for 48 hours is better than 24 and 72 hours.
Arabica coffee from Kerinci [24]	-	- Fermentation time significantly increases antioxidant activity
Arabica [25]	-	- Fine grinding and extraction yield in fermented specialty coffee preparation leads to higher antioxidant activity, with French press coffees having the highest polyphenols and Hario V60 coffees having the highest flavonoids.
Arabica [26]	*Aspergillus oryzae*	- Fermentation for 24 hours presented an increase of 115.7% and 66.4% of the antioxidant activity measured by DPPH - Increase of 68.6% in the content of phenolics and an increase of chlorogenic and caffeic acids
Liberica [27]	Liberica coffee cherry extract	- Caffeine decreased to 0.12% - Antioxidant activity increased with IC_{50} 27.27 ppm
Ipanema Brazilian Coffee [28]	Yeast *Saccharomyces species*	- Water content decreases to 1.30 – 1.23 % - Total phenols increased to 1.30 - 1.11 GAE mg mL^{-1} coffee extract
Robusta [29]	Microbial cocktail (Lactic acid bacteria and yeast)	- Total phenols increased to 383.24 mg GAE 100 g^{-1} - Antioxidant activity increased to 170.71%
Arabica [29]	Cocktail yeast	- Total phenols increased to 279.19 mg GAE 100 g^{-1} - Antioxidant activity increased by 90.35%

Likewise, Arabica coffee treated with a yeast cocktail sees a rise in total phenol content to 279.19 mg GAE 100 g^{-1}, accompanied by a substantial 90.35% boost in antioxidant activity [29]. These findings underscore the diverse ways fermentation methods influence the antioxidant landscape of different coffee varieties.

Certain antioxidants impacted by SIAF vary depending on the coffee bean matrix and the microorganisms involved in the fermentation process. An investigation into the SIAF in coffees grown at different altitudes discovered differences in the overall amount of polyphenols and their ability to fight oxidation, highlighting the impact of the approach on specific antioxidants, specifically polyphenols. The analysis emphasized the multifaceted relationship between SIAF, antioxidants, and sensory features. The flavor characteristics of coffee were influenced by temperature and fermentation duration [31]. SIAF in coffee affects certain antioxidants such as phenolic compounds, organic acids, and tannins. SIAF significantly affected coffee beans' microbial diversity, metabolic profile, and sensory characteristics. These factors are directly associated with the antioxidant qualities of coffee [9].

Moreover, the length and circumstances of SIAF play a crucial role in determining the antioxidant qualities of coffee beans, affecting functional features like the level of caffeine in anaerobic coffees [6]. Different fermentation techniques exert significant control over the antioxidant characteristics within the coffee species domain. Fermentation for 48 hours of Robusta coffee with a combination of Bacillus subtilis and Saccharomyces cerevisiae in sugarcane and banana juice yielded superior results compared to the 24-hour and 72-hour fermentation periods [23]. The combination significantly increased antioxidant activity, total polyphenol, and total flavonoid content. In the case of Arabica coffee from Kerinci, expanding fermentation time contributes an essential part in boosting antioxidant activity [24].

Meanwhile, the preparation of fermented specialty Arabica coffee determines antioxidant outcomes. Finer grinding and extraction resulted in higher antioxidant activity, with French press coffees excelling in polyphenols and Hario V60 coffees leading in flavonoids [25]. Another study also showed that coffee arabica fermented with *Aspergillus oryzae* for 24 hours significantly increased antioxidant activity, phenolic content, chlorogenic acid, and caffeic acid [26]. Understanding the antioxidants that are impacted and the resulting changes in antioxidants caused by SIAF is crucial. Previous research has suggested a possible link between self-induced anaerobic fermentation and antioxidants. However, the specific antioxidants that are impacted and the patterns and variations observed are influenced by factors such as coffee variety, cultivation altitude, and the conditions of the fermentation process.

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The impact of SIAF on the antioxidant content of coffee beans is a complex process shaped by microbial activity and fermentation conditions. A recent study has shown the impact of SIAF on coffee beans' antioxidants and function. However, additional investigation is necessary to thoroughly understand the individual antioxidants affected and the underlying mechanisms involved. Improving coffee fermentation procedures and creating beans with improved antioxidant qualities require advanced knowledge of the variations in antioxidants brought on by SIAF [6,15,30]. Additional investigation is needed to thoroughly understand the mechanisms underlying those changes and optimize the SIAF process to improve coffee's antioxidant properties.

Antioxidant Enhancement Mechanisms on Coffee Self-Induced Anaerobic Fermentation

Fermentation enhances the antioxidant activity in plant-based foods by promoting elevated levels of phenolic compounds and flavonoids, facilitating the structural breakdown of plant cell walls, and influencing the production of various enzymes [31]. The presence of SIAF has been seen to exert a substantial influence on the antioxidant composition of coffee beans. Coffee processing and influencing factors are illustrated in Figure 2.

The rise in quantity is attributed to synthesizing phenolic compounds during fermentation. Coffee beans have high levels of phenolic chemicals, recognized for their antioxidant qualities. During SIAF, the rise in phenolic compounds is believed to result from the degradation of chlorogenic acid (CGAs), a prominent phenolic molecule found in coffee beans, into smaller, more readily absorbed metabolites [9,15]. CGAs demonstrate antioxidant and antimicrobial activities, resulting from ester bonds between cinnamic acids and quinic acid. Their antioxidant effects encompass removing reactive oxygen species, such as alkyl radicals, and preventing low-density lipoprotein oxidation [26].

Throughout SIAF, there is a substantial alteration in the microbial composition of coffee beans. LAB are the primary microorganisms present during SIAF. These bacteria are recognized for their ability to generate various enzymes that facilitate the decomposition of complicated compounds into simpler forms. These enzymes are believed to have a crucial function in the degradation of chlorogenic acid and synthesizing phenolic compounds during SIAF [9,15,31]. The presence of indigenous bacteria, specifically heterofermentative LAB, significantly affects the antioxidant activity.

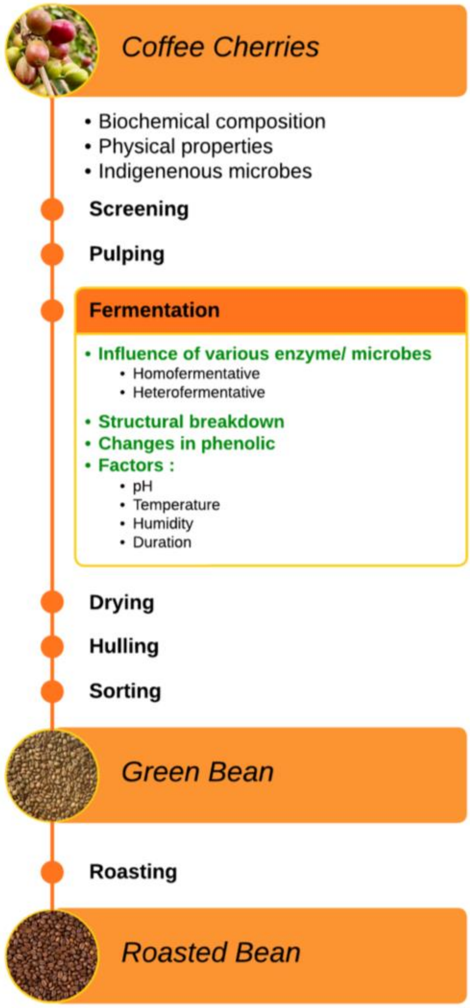

Figure 2. Coffee Processing and Influencing Factors

Heterofermentative LAB such as Leuconostoc, Oenococcus, and Lactobacillus strains have the ability to carry out various uncommon fermentation reactions, such as malolactic fermentation, pyruvate fermentation, and citrate fermentation, to produce valuable products for food biotechnology and microbiology [32]. These bacteria play a crucial role in improving the antioxidant potential of coffee by converting phenolic compounds into other compounds with higher antioxidant activity through hydrolysis and deglycosylation processes [33]. LAB can break down complex phenolic compounds into simpler forms by hydrolysis. Among the enzymes involved, feruloyl-esterase stands out for its ability to convert methyl ferulate into ferulic acid. The presence of additional hydroxyl groups in the

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structure of ferulic acid leads to an increased quantity of phenolic content and boosts antioxidant activity [34]. The fermented coffee pulp exhibited enhanced antioxidant activity, with an increase ranging from 72% to 81.8%, depending on the specific LAB strain utilized [37].

The biochemical and enzymatic processes involved in SIAF are complex and must be comprehensively explored. Nevertheless, it is shown that SIAF induces modifications in the chemical composition of coffee beans, including modifications in the levels of sugars, organic acids, and bioactive compounds [9]. Phenolic content significantly influences antioxidant activity, attributing the correlation to hydroxyl groups (-OH) [32]. Therefore, a rise in phenolic content results in a corresponding improvement in antioxidant activity. Structural modifications in phenolic compounds caused by enzymatic activity can enhance antioxidant activity. Quercetin has higher antioxidant activity than catechin, which can be linked to a double bond in its benzene ring structure despite both compounds having an identical number of hydroxyl groups [33].

In addition, the increase in phenolic content can be attributed to the action of endogenous enzymes, such as pectinase, the endogenously synthesized by plant cells or microorganisms. Pectinase can potentially diminish the pectin in the cellular wall, thereby enhancing the efficiency of extracting phenolic chemicals [9,36]. Additionally, it is attributed to the breakdown of esters bound to the cell walls. This process promotes the liberation of phenolic compounds, making them easier to access and extract after the roasting process [26,28,37]. Extended fermentation durations might result in higher amounts of polyphenolic chemicals due to the breakdown of polymerized active components. A fermentation time lasting 24 hours may reduce the phenolic content due to the formation of larger, less soluble polymerized molecules. Prolonging the fermentation process to 48 hours may increase the total phenolic contents by encouraging depolymerization and forming further soluble chemicals [8,38,39].

Moreover, the decline in antioxidant activity may be attributed to the utilization of different bacterial strains and differences in fermentation conditions. The homofermentative LAB, specifically Lactobacillus plantarum, has a more limited metabolic route than the heterofermentative LAB. Homofermentative LAB utilizes glycolysis and lactate dehydrogenase processes to ferment hexoses into lactic acid. Under slow growth conditions and low glycolytic flux rates, homofermentative bacteria transition to mixed acid fermentation, producing formate, acetate, ethanol, and lactate as end products [34]. Homofermentative LAB lacks the enzymes required to convert or modify phenolic compounds, consequently affecting their antioxidant activity [40].

Moreover, a prolonged period of fermentation (exceeding 72 hours) might also diminish the antioxidant activity, leading to a decline in the phenolic content. The reduction is attributed to the activity of polyphenol oxidase enzymes, which promote the dispersion and oxidation of phenolics in cell liquids [8,38,39].

Existing theories on the mechanisms behind antioxidant improvement during SIAF are based on limited research, and knowledge gaps still exist [15]. In this regard, the way chlorogenic acid breaks down into smaller and more bioavailable substances that occur during SIAF is not yet clear [9,41]. Additional investigation is required to comprehensively understand the biochemical and enzymatic mechanisms involved in SIAF and their influence on the antioxidant composition of coffee beans.

Several microorganisms throughout the process of anaerobic coffee fermentation have been discovered to greatly influence the overall quality and safety of coffee production. The quality of coffee produced on farms with inadequate facilities can be significantly enhanced by manipulating the fermentation conditions to enhance the proliferation of dominant microbes. Factors such as sugars, fermentation temperature, duration, and oxygen concentration have been recognized as environmental parameters that impact the fermentation process and, consequently, the flavor attributes of coffee [6,16,42].

SIAF, being an innovative technology, drastically enhances the antioxidants in coffee beans. The proposed mechanisms involve the production of phenolic compounds during fermentation, potentially attributed to the breakdown of chlorogenic acid by lactic acid bacteria. The significant influence of microbial diversity and fermentation conditions on coffee's flavor, quality, and safety is evident. The biochemical and enzymatic processes in SIAF are complex and unknown, highlighting the need for additional research to fully comprehend the mechanisms responsible for improving antioxidants in this fermentation method.

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CONCLUSION

The study of SIAF and its effects on the antioxidants found in coffee has revealed groundbreaking and important discoveries. SIAF is a method that increases the antioxidants in coffee beans. This process enhances the presence of compounds by facilitating interaction among microbial activity, enzymatic processes, and changes in chemical composition. As a result, it leads to a distinctive profile of antioxidants. By emphasizing the potential of SIAF to enhance coffee nutrition and health-related characteristics, this study highlights the potential of SIAF in the coffee industry and promotes innovation within it. More research is necessary to understand particular mechanisms and achieve desired results, so cooperative efforts are encouraged to continue this field's exploration.

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REFERENCES

[1] Alves. R.C., F. Rodrigues, M.A. Nunes, A.F. Vinha, M. Beatriz, P.P. Olivera. 2017. Chapter 1. State of the art in coffee processing by-products in coffee processing by-products. In: Sustainable Applications. Academic Press. New York. 1–26. DOI: 10.1016/B978-0-12-811290-8.00001-3.

[2] Sunarharum, W.B., K. Fibrianto, S.S. Yuwono, M. Nur. 2019. Sains Kopi Indonesia. UB Press. Malang.

[3] Komes D., A. Bušić. 2014. Antioxidants in Coffee. In: Process and Impact on Antioxidants in Beverages. Academic Press. United States. 25–32. DOI: 10.1016/B978-0-12-404738-9.00003-9.

[4] Zhang, C., C. Wang, F. Liu, Y. He. 2016. Mid-infrared spectroscopy for coffee variety identification: Comparison of pattern recognition methods. *J. Spectrosc.* 1–8. DOI: 10.1155/2016/7927286.

[5] Braga, A.V.U., M.A. Miranda, H. Aoyama, F.L. Schmidt. 2023. Study on coffee quality improvement by self-induced anaerobic fermentation: Microbial diversity and enzymatic activity. *Food Res. Int.* 165. 1–14. DOI: 10.1016/j.foodres.2023.112528.

[6] Halagarda, M., P. Obrok, 2023. Influence of post-harvest processing on functional properties of coffee (*Coffea arabica* L.). *Molecules.* 28(21). 1–9. DOI: 10.3390/molecules28217386.

[7] Kim, D.H., S.J. Yeon, K.I. Jang. 2016. Quality characteristics and antioxidant activity of espresso coffee prepared with green bean fermented by lactic acid bacteria. *J. Korean Soc. Food Nutr.* 45(12). 1799–1807. DOI: 10.3746/jkfn.2016.45.12.1799.

[8] Haile, M., W.H. Kang. 2019. Antioxidant activity, total polyphenol, flavonoid and tannin contents of fermented green coffee beans with selected yeasts. *Fermentation.* 5(1). 1–13. DOI: 10.3390/fermentation 5010029.

[9] Da Silva-Vale, A., G. Balla, L.R.S. Rodrigues, D.P. de Carvalho-Neto, C.R. Soccol, G.V. de Melo-Pereira. 2023. Understanding the effects of self-induced anaerobic fermentation on coffee beans quality: microbiological, metabolic, and sensory studies. *Foods.* 12(1). 1–20. DOI: 10.3390/foods12010037.

[10] Pereira, T.S., N.N. Batista, L.P.S. Pimenta, S.J. Martinez, L.S. Ribeiro, J.A.O. Naves, R.F. Schwan. 2021. Self-induced anaerobiosis coffee fermentation: Impact on microbial communities, chemical composition and sensory quality of coffee. *Food Microbiol.* 103. 1–11. DOI: 10.1016/j.fm.2021.103962.

[11] Hidayati, D. 2010. Pola pertumbuhan bakteri asam laktat selama fermentasi susu kedelai. *Jurnal Teknologi Hasil Pertanian.* 3(2). 72–76. DOI: 10.20961/jthp.v0i0.13630.

[12] Wilujeng, A.A.T., P.R. Wikandari. 2013. Pengaruh lama fermentasi kopi arabika (*Coffea arabica*) dengan bakteri asam laktat *Lactobacillus plantarum* B1765 terhadap mutu produk. *UNESA Journal of Chemistry.* 2(3). 1–10.

[13] Ribeiro, L.S., M.G. da Cruz-Pedrozo Miguel, S.J. Martinez, A.P.P. Bressani, S.R. Evangelista, C.F.S.E. Batista, R.F. Schwan. 2020. The use of mesophilic and lactic acid bacteria strains as starter cultures for improvement of coffee beans wet fermentation. *World J. Microbiol. Biotechnol.* 36(12). 1–15. DOI: 10.1007/s11274-020-02963-7.

[14] da Silva, B.L., P.V. Pereira, L.D. Bertoli, D.L. Silveira, N.N. Batista, P.F. Pinheiro, *et al.* 2021. Fermentation of *Coffea canephora* inoculated with yeasts: Microbiological,

chemical, and sensory characteristics. *Food Microbiol.* 98. 1–9. DOI: 10.1016/j.fm.2021. 103786.

[15] da Mota, M.C.B., N.N. Batista, D.R. Dias, R.F. Schwan. 2022. Impact of microbial self-induced anaerobiosis fermentation (SIAF) on coffee quality. *Food Biosci.* 47. 1–10. DOI: 10.1016/j.fbio.2022.101640.

[16] Lee, B.H., C.H. Huang, T.Y. Liu, J.S. Liou, C.Y. Hou, W.H. Hsu. 2023. Microbial diversity of anaerobic-fermented coffee and potential for inhibiting ochratoxin-produced *Aspergillus niger*. *Foods.* 12(15). 1–17. DOI: 10.3390/foods12152967.

[17] Lestari, W., K. Hasballah, M.Y. Listiawan, Sofia. 2022. Coffee by-products as the source of antioxidants: A systematic review. 11. 1–12. F1000Res. DOI. 10.12688/ f1000research.107811.1.

[18] Yashin, A., Y. Yashin, J.Y. Wang, B. Nemzer, 2013. Antioxidant and antiradical activity of coffee. *Antioxidants.* 2(4). 230–245. DOI: 10.3390/antiox2040230.

[19] Pérez-Burillo, S., T. Mehta, A. Esteban-Muñoz, S. Pastoriza, O. Paliy, J.Á. Rufián-Henares. 2019. Effect of in vitro digestion-fermentation on green and roasted coffee bioactivity: The role of the gut microbiota. *Food Chem.* 279. 252–259. DOI: 10.1016/ j.foodchem.2018.11.137.

[20] Messina, G., C. Zannella, V. Monda, A. Dato., D. Liccardo, S. De Blassio, *et al.* 2015. The beneficial effects of coffee in human nutrition. *Biol. Med.* 7(4). 1–5. DOI: 10.4172/0974-8369.1000240.

[21] Chiang, H.M., C.W. Chen, C.C. Chen, H.W. Wang, J.H. Jhang, Y.H. Huang, K.C. Wen. 2015. Role of *Coffea arabica* extract and related compounds in preventing photoaging and photodamage of the skin. In: Coffee In Health and Disease Prevention. 523-530. DOI: 10.1016/B978-0-12-409517-5.00058-9.

[22] Liang, N., D.D. Kitts. 2014. Antioxidant property of coffee components: Assessment of methods that define mechanism of action. *Molecules.* 19(11). 180–208. DOI: 10.3390/molecules191119180.

[23] Dinh, Y.N., Q.D. Nguyen, H.P. Le. 2022. Investigation of changes of antioxidant properties of coffee through fermentation by using *Saccharomyces cerevisiae* and *Bacillus subtilis*. *J. Tech. Edu. Sci.* 17(01). 72–79. DOI: 10.54644/jte.70B.2022.1174.

[24] Nizori, A., E. Jayanti, S. Suharini, I. Gusriani, M. Mursyid, D.T. Purba. 2021. Influence of fermentation conditions on the antioxidant and physico-chemical of arabica coffee from Kerinci Region of Indonesia. *Indonesian Food Sci. Technol. J.* 5(1). 34–38. DOI: 10.22437/ifstj.v5i1.17383.

[25] Várady, M., J. Tauchen, P. Klouček, P. Popelka. 2022. Effects of total dissolved solids, extraction yield, grinding, and method of preparation on antioxidant activity in fermented specialty coffee. *Fermentation.* 8(8). 1–9. DOI: 10.3390/ fermentation8080375.

[26] Palmieri, M.G.S., L.T. Cruz, F. Bertges, H.M. Hungaro, L.S. Batista, S.S. da Silva, *et al.* 2018. Enhancement of antioxidant properties from green coffee as promising ingredient for food and cosmetic industries. *Biocatal. Agric. Biotechnol*. 16. 43–48. DOI: 10.1016/j.bcab.2018.07.011.

[27] Sunarharum, W.B., H.R. Umami, A.A. Kartika, S. Septiana, T. Mahatmanto. 2023. Re-fermentation of green liberica coffee (*Coffea liberica*) beans: Impact on the caffeine and antioxidant content of the roasted beans. *J. Exp. Life Sci.* 13(2). 67–69. DOI: 10.21776/ub.jels.2023.013.02.001.

[28] Kwak, H.S., Y. Jeong, M. Kim. 2018. Effect of yeast fermentation of green coffee beans on antioxidant activity and consumer acceptability. *J. Food Qual.* 1–9. DOI: 10.1155/2018/5967130.

[29] Therdtatha, P., N. Jareontanahun, W. Chaisuwan, K. Yakul, A. Paemanee, A. Manassa, *et al.* 2023. Production of functional Arabica and Robusta green coffee beans: Optimization of fermentation with microbial cocktails to improve antioxidant activity and metabolomic profiles. *Biocatal. Agric. Biotechnol.* 53. 1–16. DOI: 10.1016/ j.bcab.2023.102869.

[30] Martinez, S.J., N.N. Batista, A.P.P. Bressani, D.R. Dias, R.F. Schwan. 2022. Molecular, chemical, and sensory attributes fingerprinting of self-induced anaerobic fermented coffees from different altitudes and processing methods. *Foods.* 11(24). 1–16. DOI: 10.3390/foods11243945

[31] Hur, S.J., S.Y. Lee, Y.C. Kim, I. Choi, G.B. Kim. 2014. Effect of fermentation on the antioxidant activity in plant-based foods. *Food Chem.* 160. 346–356. DOI: 10.1016/ j.foodchem.2014.03.112.

ISSN. 2087-2852
E-ISSN. 2338-1655

[32] Zaunmüller, T., M. Eichert, H. Richter, G. Unden. 2006. Variations in the energy metabolism of biotechnologically relevant heterofermentative lactic acid bacteria during growth on sugars and organic acids. Appl. Microbiol. Biotechnol. 72(3). 421–429. DOI: 10.1007/s00253-006-0514-3.

[33] Zhao, D., N.P. Shah. 2016. Lactic acid bacterial fermentation modified phenolic composition in tea extracts and enhanced their antioxidant activity and cellular uptake of phenolic compounds following in vitro digestion. *J. Funct. Foods.* 20(13). 182–194. DOI: 10.1016/j.jff.2015.10.033.

[34] Rodríguez, L.G.R., V.M.Z. Gasga, M. Pescuma, C.V. Nieuwenhove, F. Mozzi, J.A.S. Burgos. 2021. Fruits and fruit by-products as sources of bioactive compounds. Benefits and trends of lactic acid fermentation in the development of novel fruit-based functional beverages. Food Res. Int. 140. 1–17. DOI: 10.1016/j.foodres.2020.109854.

[35] López, T., A. Prado-Barragán, G.V. Nevárez-Moorillón, J.C. Contreras, R. Rodríguez, C.N. Aguilar. 2013. Incremento de la capacidad antioxidante de extractos de pulpa de café por fermentación láctica en medio sólido. CYTA – *J. Food.* 11(4). 359–365. DOI: 10.1080/19476337.2013.773563.

[36] Ruviaro, A.R., P. de Paula-Menezes-Barbosa, G.A. Macedo. 2019. Enzyme-assisted biotransformation increases hesperetin content in citrus juice by-products. *Food Res. Int.* 124. 213–221. DOI: 10.1016/ j.foodres.2018.05.004.

[37] Shi, M., Y. Yang, Q. Wang, Y. Zhang, Y. Wang, Z. Zhang. 2012. Production of total polyphenol from fermented soybean curd residue by *Lentinus edodes*. *Int. J. Food Sci. Technol.* 47(6). 1215–1221. DOI: 10.1111/ j.1365-2621.2012.02961.x.

[38] Haile, M., W.H. Kang. 2020. Antioxidant properties of fermented green coffee beans with *Wickerhamomyces anomalus* (Strain KNU18Y3). *Fermentation.* 6(1). 1–16. DOI: 10.3390/fermentation6010018.

[39] Chu, S.C., C. Chen. 2006. Effects of origins and fermentation time on the antioxidant activities of kombucha. *Food Chem.* 98(3). 502–507. DOI: 10.1016/j.foodchem.2005. 05.080.

[40] Ankolekar, C.R. 2013. Lactic acid bacteria mediated phenolic bioactive modulation from fruit systems for health benefits. Disertation. Department of Food Science. University of Massachusetts Amherst. USA.

[41] do Rosário, D.K.A., Y. da Silva Mutz, K.M. Vieira, R.F. Schwan, P.C. Bernardes. 2023. Effect of self-induced anaerobiosis fermentation (SIAF) in the volatile compounds and sensory quality of coffee. *Eur. Food Res. Technol.* 250(2). 667–675. DOI: 10.1007/s00217-023-04393-9.

[42] Fakhruddin, A.A., I.S. Roidah. 2023. Inovasi produk olahan kopi dengan cita rasa buah-buahan pada LMDH Watu Blorok KPH Mojokerto. *Jurnal Kabar Masyarakat.* 1(3). 110–119. DOI: 10.54066/jkb. v1i3.558.