

The impact of coffee in athletics: a comprehensive review of its components, sensory attributes and implications for sports health

Runqing He *

Shanghai Pinghe School, Shanghai, 200120, China

* Corresponding Author Email: herunqing@shphschool.com

Abstract. This comprehensive review explores coffee's diverse impact on athletics, covering its bioactive elements, sensory qualities, and effects on sports performance and health. It examines coffee's potential benefits and challenges in sports health, encompassing physical fitness, mental well-being, nutrition, injury prevention, and recovery. The review first investigates key bioactive compounds in coffee, including polyphenols (e.g., caffeic acid, chlorogenic acids), caffeine, and bioflavonoids. It discusses how these compounds contribute to enhanced sports performance and overall health. The review highlights caffeine's impact on alertness, endurance, and recovery, emphasizing optimal dosages and potential discomfort at higher levels. Additionally, it underscores the antioxidative properties of chlorogenic acids, which can mitigate oxidative stress and inflammation, supporting neuronal protection and injury recovery. The sensory experience of coffee, including taste and aroma, is also explored for its psychological influence on sports performance and health. The review addresses potential risks linked to coffee consumption, emphasizing the importance of moderation in the context of sports health. Concluding, the review identifies research gaps and suggests areas for future exploration. This comprehensive analysis underscores coffee's multi-dimensional role in athletics, spanning its bioactive components and sensory qualities, shedding light on its potential to enhance sports performance and overall well-being.

Keywords: Coffee; athletics; sports health; review.

1. Introduction

Coffee, a daily beverage savored by millions, has become a staple in athletes' diets worldwide since the World Anti-doping Agency decided to delist caffeine as a banned substance (Agency, 2003). This pivotal decision allowed athletes to consume moderate caffeine via various sources without concern for anti-doping violations. Through data-driven insights, the scientific community strives to decode the intricate interplay between coffee and human health, providing individuals with a lucid blueprint to navigate their caffeine journey.

Research has extended into evaluating the broad implications of different coffee intake levels, focusing on human performance, caffeine toxicity thresholds, and its adverse reaction spectrum (Maridakis et al., 2009; Nehlig, 2010). Investigations have also aimed to pinpoint the optimal quantity of caffeine in coffee and identify other beneficial constituents that enhance athletic performance and overall health (Hu et al., 2019). Beyond uncovering the molecular mechanisms through which coffee amplifies performance, there has been a keen discerning the variances in caffeine's efficacy across diverse exercise modalities.

The burgeoning adoption of coffee among athletes is not merely due to its energizing effects but also owes to its myriad of bioactive compounds and nuanced flavors. These compounds collectively demonstrate the potential to elevate muscle endurance, modulate perceived exertion, and sharpen concentration and alertness (Pickering & Grgic, 2020). However, previous discussions have sidestepped mainly the influence of coffee flavor on sports health, leading to a somewhat skewed understanding of how coffee's sensory experience might intertwine with athletic outcomes.

Based on these findings, this review will provide an overview of the existing research on the composition of coffee and its impact on athletic health. The author will illuminate the precise

proportions of crucial coffee constituents essential for human well-being and delve into a lesser-explored territory: the potential role of coffee's flavor palette in influencing athletic performance.

2. Sports Health: An Intertwined Relationship

In the context of this article, "sports health" is delineated as the intricate fusion of sports and health and their reciprocal influences on one another. The symbiotic relationship between physical activity and holistic well-being is undeniable.

Moderate physical activity can yield a plethora of benefits (Posadzki et al., 2020). Aerobic exercise, for instance, bolsters the cardiovascular system, while weight training activities play a pivotal role in enhancing bone density (Moreira et al., 2020). Furthermore, specific exercises have been linked with a fortified immune function (Nieman, 2021). These physical gains, however, are complemented by profound psychological advantages. The release of neurochemicals such as endorphins and dopamine during physical exertion has a multifaceted role. Not only do they act as mood regulators, assisting in emotion management, but they also serve as catalysts in enhancing self-worth, fostering self-confidence, and fortifying mental resilience (Brinsley et al., 2022).

Conversely, an individual's health status can delineate the type and intensity of physical activity they can or should engage in. Health problems require appropriate medical advice and exercise programs, and issues such as injuries or fluctuating energy levels can also affect the willingness and ability to exercise (Booth et al., 2022). To sum up, exercise and health promote each other; reasonable exercise habits not only enhance physical fitness and reduce the risk of disease but also improve the psychological state and quality of life. In essence, the relationship between exercise and health is bidirectional. While appropriate physical activities amplify physical vitality and mitigate disease risk, they simultaneously uplift psychological well-being, thereby elevating overall life quality.

3. The Wealth of Main Bioactive Compounds in Coffee

In the realm of sports and physical exertion, coffee has been recognized as a significant ergogenic tool, affirming its place among athletes and fitness professionals. The benefits of coffee extend beyond mere stimulation, offering a multifaceted spectrum of advantages.

3.1. Caffeine and Sports Performance

Undeniably, when considering the active constituents of coffee, caffeine often reigns supreme in our collective psyche. Found in proportions of approximately 0.9-1.3 g/100 g of coffee, caffeine has been scientifically validated as a stimulant for the central nervous system, resulting in increased focus, alertness, and physical output (Burke, 2008; Farah, 2012).

A breadth of research highlights caffeine's enhancement of exercise outcomes in various domains, from aerobic endurance to muscular strength (Anselme et al., 1992; Mesquita et al., 2020; Warren et al., 2010). The efficacy of these effects can differ based on the sport type and the caffeine dosage. For example, Bridge and Jones revealed a marked enhancement in race times for distance runners post caffeine consumption (Bridge & Jones, 2006). Similarly, Jenkins et al. (Jenkins et al., 2008) demonstrated how varying doses of caffeine could significantly improve cycling performance, reinforcing its positive influence on aerobic activities. On the anaerobic front, caffeine has been illustrated to bolster maximal power during short sprints, albeit with an associated spike in lactic acid levels, hinting at potential post-exercise muscle discomfort (Anselme et al., 1992). However, the efficacy of caffeine in team sports remains equivocal, as evinced by studies on football players that demonstrated metabolic shifts without performance improvements (Bassini et al., 2013).

The biochemical mechanisms underlying the exercise-related effects of caffeine are complex and not yet fully understood. However, specific cellular processes that may illuminate or contribute to these effects have been identified. The performance-enhancing effects of caffeine during sports and exercise are primarily attributed to its interaction with adenosine receptors in the central nervous

system (Davis et al., 2003; Fredholm et al., 1999). Adenosine receptors are often associated with inhibitory signaling, and caffeine acts as an antagonist of adenosine receptors, blocking their activation. This means that the presence of caffeine can reduce inhibitory signaling, thereby increasing neuronal excitability and neurotransmitter release (Fiani et al., 2021). This leads to increased alertness, attention, and neural activity, explaining why caffeine promotes wakefulness. Concurrently, caffeine's effect on adenosine receptors may influence blood flow, particularly during exercise, enhancing oxygen and nutrient delivery to muscles and thus improving performance and delaying fatigue (Davis & Green, 2009; Meeusen et al., 2013; Jiménez et al., 2021). Caffeine also stimulates catecholamine release, thereby increasing arousal. This ancestral trait can positively influence sports performance by elevating circulating glucose levels, cardiac output, and blood flow to the working muscles (Papadelis et al., 2003). Furthermore, caffeine has been observed to amplify the release of beta-endorphins during exercise, potentially contributing to an elevated tolerance for physical exertion (Barcelos et al., 2020).

Caffeine's influence is not restricted to the central nervous system; it also directly affects skeletal muscles through interaction with ryanodine receptors, increasing calcium release and excitation-contraction coupling, resulting in better muscle contractions (Grgic et al., 2018; Warren et al., 2010). This can help muscles achieve higher power output with fewer recruited fibers, potentially delaying fatigue (Tallis et al., 2015). However, higher caffeine concentrations are needed compared to adenosine receptor blockade. This intricate process can lead to heightened muscle excitability and strength (Warren et al., 2010). While this offers potential, it can also disrupt homeostasis and increase muscle damage due to intensified workload. In translating these findings to sports, caution is needed due to potential toxic effects at higher caffeine doses. This balance between performance benefits and risks is crucial. (Barreto et al., 2021).

Current consensus suggests an optimal caffeine dose of 3mg/kg body weight for athletic enhancement (Nehlig, 2010; van Dam et al., 2020). For a 70 kg individual, this equates to approximately 210 mg of caffeine or two average-sized cups of coffee. Some evidence indicates that doses up to 6mg/kg may offer even more significant benefits (Del Coso et al., 2013; Fett et al., 2017; Lara et al., 2014), but individual variations such as genetics, tolerance, and absorption must be considered to determine the optimal dosage. Excessive caffeine consumption's potential side effects should also be kept in mind. In conclusion, the relationship between caffeine and sports performance is intricate but undeniably correlated with improved athletic outcomes. Nevertheless, individual differences and potential side effects must be considered when determining the optimal dosage for each athlete.

3.2. Antioxidants in Coffee: Beyond Caffeine

Coffee is more than just a source of caffeine. It is also a rich polyphenol reservoir, including flavonoids and phenolic acids. These compounds give coffee its antioxidant properties, which protect cellular structures from the detrimental effects of free radicals.

3.2.1. Significance of Chlorogenic Acids (CGAs)

Chlorogenic acids (CGAs), representing the polyphenolic family, are formidable antioxidants in coffee. They have been associated with various health benefits, from anti-inflammatory properties to fortifying heart health (Lu et al., 2020). Especially green coffee beans have a CGA content of about 6-12% by weight, underscoring their significance in these beans.

The antioxidant properties of CGA stem from their molecular structures, allowing them to neutralize oxidizing agents. Six primary isoforms of CGAs demonstrate a protective effect on DNA, countering damages caused by agents like H₂O₂ and NH₂Cl. A significant antioxidant activity of 5-CQA, one of the CGAs, is its defense against LDL oxidation – an early step in atherosclerosis development.

3.2.2. Prevalence and Biological Impact of 5-CQA in Coffee

The most abundant CGA in coffee is 5-CQA, which accounts for 76-84% of the total CGAs in green coffee beans and other plants. According to Mills et al. (2013), freshly ground and instant coffee contain significant amounts of 5-CQA. The prominence of this compound has prompted extensive studies, revealing its plethora of biological and pharmacological activities.

5-CQA has a multifaceted positive impact on various physiological processes and body systems. Its potential is vast, from being anti-inflammatory to exhibiting anti-tumor properties and even displaying protection for the gastrointestinal tract (Naveed et al., 2018). It has significant anti-inflammatory properties, inhibiting the release of inflammatory mediators, which in turn promotes vascular health and inhibits the development of atherosclerosis (Johnson, 2019). This attribute becomes evident during physical exertion. The body might undergo a transient inflammatory retort following exercise, predominantly within muscular tissues. The presence of 5-CQA can attenuate or abbreviate this inflammatory reaction via its inherent capacity to perpetually discharge anti-inflammatory mediators. Consequently, this property assists in expediting the restitution of muscular functionality.

Moreover, its ability to cross the blood-brain barrier further emphasizes its significance, especially considering its protective effects on the nervous system. During exercise, particularly following prolonged or high-intensity sessions, cognitive fatigue and stress on the nervous system could pose challenges. However, 5-CQA has the potential to alleviate these impacts through such mechanisms, thereby enhancing athletic performance and expediting recovery rates. (Pingitore et al., 2015),

Researchers have investigated 5-CQA's antioxidant properties in various models. Key findings include its role in reducing apoptosis in primary cortical neurons, increasing the activity of specific enzymes, and protecting against oxidative stress (Upadhyay & Mohan Rao, 2013). A very typical example is that 5-CQA exerts its neuroprotective effects against attention deficit disorder by inhibiting the activity of two key enzymes, acetylcholinesterase (ACHE) and butyrylcholinesterase (BCHE), as well as by suppressing oxidative stress-induced neuronal damage. Animal models have further verified the antioxidant properties of CGAs. They have been shown to mitigate the hyperglycemic side effects seen in diabetes and to attenuate oxidative stresses induced by environmental pollutants and other harmful agents (Tajik et al., 2017). In the field of nephroprotection, 5-CQA is promising because of its antioxidant and anti-inflammatory properties, which may help control kidney damage (Liang & Kitts, 2016). In the context of physical exertion, oxidative stress has the potential to induce cellular detriment, muscle fatigue, immune system impairment, and instigate inflammatory responses (Pingitore et al., 2015; Sies et al., 2017). In counteraction, the application of 5-CQA exhibits a dual mechanism of mitigating oxidative stress. It achieves this by quenching free radicals and augmenting the enzymatic activity of endogenous antioxidant defenses within cellular compartments. Consequently, this orchestrated response serves to bolster cellular resilience against the inception and progression of oxidative stress phenomena (Amigoni et al., 2017).

5-CQA is a powerful safeguard for the health of the gastrointestinal tract due to its cytoprotective effects against diseases such as gastric ulcers and inflammatory bowel disease. Its ability to modulate neutrophil influx, inflammatory mediators, and antioxidant properties helps protect the gastric mucosa and mitigate oxidative damage in the gut. The compound also has the potential to treat and prevent a wide range of gastrointestinal diseases and is a potential alternative to antibiotics (Shimoyama et al., 2013). Similarly, the hepatoprotective potential of 5-CQA is outstanding, preventing hepatic fibrosis, hepatic steatosis, and acute liver injury. (Lu et al., 2020) Its mechanism includes inhibition of oxidative stress, reduction of inflammatory response, promotion of autophagy, and activation of antioxidant pathways such as NFE2L2 (Naveed et al., 2018). In addition, the newly developed 5-CQA lipid formulation has higher bioavailability and potential for targeted liver protection. In addition, 5-CQA is involved in the treatment of diabetes and metabolic syndrome by modulating lipid and glucose metabolism, combating NAFLD, and addressing hyperglycemia. As an anticancer agent, it also has significant potential to inhibit the growth of various cancer cell lines by

modulating apoptosis, inhibiting oxidative stress, interfering with signaling, and inducing cell differentiation (Shi et al., 2016).

Cardiovascular well-being regulates oxygen transport and endurance; liver function impacts metabolism and waste elimination; muscular strength facilitates movement; and neural stability coordinates motor control—highlighting their essential contributions to exercise-related health. 5-CQA, through various pathways, can effectively mitigate the occurrence of these aspects of diseases and aid in the repair of damages. Undoubtedly, this underscores the beneficial effects of 5-CQA on physical activity.

3.2.3. Other Polyphenols in Coffee

In addition to chlorogenic acids (CGAs), coffee contains various other polyphenols, such as ferulic acid, caffeic acid, and melanoidins. The following sections explore these compounds and their potential applications in sports.

Ferulic acid

Ferulic acid is recognized for its potent antioxidant abilities, which may have implications for athletes in terms of protecting against UV-induced skin damage, a concern for those training outdoors (Zduńska et al., 2018). The underlying mechanism driving this antioxidant activity is the formation of resilient phenoxy radicals. These arise from the interactions between free radical entities and antioxidant molecules, halting intricate cascade reactions and thereby preventing the formation of additional free radicals (Zduńska et al., 2018). The proficiency of ferulic acid in chelation with protonated metal ions, such as copper (II) and iron (II), further underlines its antioxidant capabilities (Rice-Evans et al., 1996). Further research may explore its role in recovery and muscle protection, given its capabilities in free radical scavenging.

Caffeic Acid

Caffeic acid's neuroprotective effects may be of interest to sports professionals, considering the focus on cognitive function and reaction time in many athletic disciplines. Caffeic acid has been shown to exhibit neuroprotective effects and is currently under investigation for its potential role in slowing the progression of neurodegenerative diseases like Parkinson's and Alzheimer's (Turan et al., 2020). Additionally, it has been found to protect α -tocopherol (vitamin E) in low-density lipoprotein (LDL) (Laranjinha et al., 1996). When combined with other compounds, such as chlorogenic and caftaric acids, caffeic acid demonstrates enhanced antioxidant efficacy across various systems (Fukumoto & Mazza, 2000). Its potential role in hindering neurodegenerative diseases could extend to protecting against sports-related brain injuries, but this connection requires more exploration.

Melanoidins

Melanoidins, synthesized during the roasting process of coffee, are of interest for their prebiotic properties, which could support gut health in athletes (Komes & Bušić, 2014; Borrelli et al., 2002). Proper digestive function is essential for nutrient absorption, which can directly affect performance and recovery. These compounds play a crucial role in the marked antioxidant and metal-chelating attributes observed in coffee extracts. Several studies have confirmed this phenomenon, attributing it to melanoidins' ability to disrupt radical chains by providing hydrogen atoms, effectively chelating metals, transforming hydroperoxides into non-radical substances, and neutralizing hydroxyl radicals (Borrelli et al., 2002; Delgado-Andrade & Morales, 2005).

4. Mental Health Benefits of Coffee

Coffee, renowned worldwide as a multifaceted health tool, has implications beyond general well-being in the specialized athletics field.

4.1. Cognitive Enhancement and Athletic Performance

At the intersection of neurology and sports, caffeine, coffee's primary alkaloid, transcends its role as a mere stimulant. It acts as an enhancer of cognitive functions essential for athletes, facilitating heightened concentration, enhanced alertness, and mood elevation. Such effects are paramount in

competitive contexts, potentially leading to superior decision-making in team sports, heightened focus in endurance pursuits, and reinforced mental tenacity in training and competition (Spriet, 2014). Emerging evidence further posits that habitual coffee consumption may confer protection against neurodegenerative conditions, safeguarding athletes' cognitive health throughout their professional journey and thereafter (Fredholm, 1979).

The effects of caffeine on learning and memory appear to vary based on the nature of the task and individual differences. Research findings suggest that the impact of caffeine on learning and memory is contingent upon the nature of the task (Jarvis, 1993). In scenarios where information is passively presented, as seen in associative learning tasks, caffeine's potential to elevate alertness and enhance attention may contribute to improved learning outcomes. Nevertheless, the effects of caffeine appear less pronounced in tasks involving deliberate material comprehension.

In terms of memory, research findings regarding short-term memory reveal varying effects of caffeine on immediate free recall tasks. While certain studies indicate no significant influence of caffeine on free recall performance, others suggest potential enhancements or even impairments. Moreover, caffeine's impact on working memory performance can be contingent on specific conditions, showing potential improvement but lacking pronounced effects in complex tasks, possibly leading to impairment. However, in the context of long-term memory, a study has demonstrated that caffeine's influence remains insignificant, even at higher dosages (Nehlig, 2010).

4.2. Protective Effects on Physical Health

True athletic prowess encompasses more than mere competition; recovery, sustained health, and disease prevention are paramount. Coffee, in this context, exhibits multifaceted health benefits. Empirical studies have postulated that moderate coffee consumption is inversely correlated with risks associated with chronic ailments such as type 2 diabetes and cardiovascular diseases (van Dam & Hu, 2005). For athletes, this translates to augmented cardiovascular efficiency and metabolic vitality, foundational for peak performance.

Given the heightened susceptibility of athletes to oxidative stress due to strenuous exertion, coffee's role in expediting recovery and curtailing inflammation is invaluable (Martínez-López et al., 2019). Such effects mitigate immediate post-activity soreness and potentially attenuate risks associated with chronic inflammation and subsequent injuries.

5. Flavors and the Sensory Experience in Coffee: Athletic Implications

The sensory characteristics of coffee, encompassing both olfaction and gustation, play a profound role in evoking various psychological and physiological reactions. This section explores the intricate relationship between these sensory experiences and their implications for athletic performance.

5.1. Conditioning and the Coffee Experience

Classical conditioning provides a framework to understand the complex interplay between sensory stimuli like coffee's aroma and the consequent psychological reactions. The aroma of coffee can trigger alertness, a response usually associated with caffeine's physiological effects (Hawiset, 2019). This phenomenon could be harnessed in sports, where the mere smell of coffee might stimulate athletes, enhancing focus and readiness. This conditioned response, however, exhibits individual variability and may depend on personal histories and established habits.

5.2. Empirical Evidence: The Influence of Coffee Aroma

Several studies have delved into the relationship between coffee aroma and cognitive functions. Hawiset's seminal study (2019) offers a comprehensive exploration of this interrelationship (Hawiset, 2019). Participants exposed to coffee aroma consistently outperformed their counterparts, exhibiting superior attention, memory retention, and alertness. Intriguingly, Madzarov et al. (2018) emphasized the psychosomatic influence of coffee aroma on task performance. These findings can have

applications in sports, where the aroma of coffee could potentially improve concentration and reaction times, aiding athletes in training and competition.

5.3. Synthesizing the Findings: Psychological versus Physiological Reactions

While it is clear that the aroma of coffee can induce a heightened state of alertness and cognitive acuity, these effects seem to hinge predominantly on psychological expectations rather than bona fide physiological reactions. This delineation is essential for understanding the multifaceted nature of coffee's impact on human cognition and performance. In essence, the world of coffee is not just about caffeine's tangible stimulatory effects but also the more subtle yet powerful, psychological implications of its rich flavors and evocative aroma.

5.4. The Sensory Complexity of Coffee: Beyond Aroma

The sensory appeal of coffee goes beyond aroma; its flavor, texture, and even temperature can influence the overall experience. Its aroma may aid in focusing the mind, while its flavors and textures could offer comfort and stimulation. Research into the relationship between these sensory attributes and cognitive or emotional states remains an emerging field. Future studies might explore how these aspects of coffee can be applied in sports settings to enhance athletes' psychological well-being or performance.

6. Considerations for Athletes

The benefits of coffee within the sporting arena are substantial, yet its application must be tailored to an athlete's unique requirements. While caffeine has been shown to enhance athletic performance (Burke, 2008), overconsumption can lead to symptoms such as jitteriness or anxiety, which may negatively affect an athlete's focus and precision during events (Spriet, 1995). Additionally, as coffee acts as a diuretic (Maughan & Griffin, 2003), athletes must be mindful of compensating for any fluids lost, especially during intensive training or competitions, to prevent dehydration. Quality sleep is paramount for recovery in athletes, and consuming coffee late in the day may disrupt sleep patterns, thereby impeding recovery and future performance (Maughan & Griffin, 2003). Some athletes experience gastrointestinal issues when consuming coffee before exercise, which can hinder performance (de Oliveira et al., 2014). Regular consumption can lead to caffeine tolerance, requiring higher doses to achieve the same effects. Thus, athletes must personalize their coffee consumption to align with their unique physiological and performance needs, being cautious to avoid dependency and recognizing withdrawal symptoms such as headaches or fatigue.

7. Conclusion and Future Research Directions

In summary, this comprehensive review has extensively examined the intricate interplay between coffee and athletics, shedding light on a broad spectrum of effects encompassing bioactive compounds and sensory attributes. Through a meticulous analysis of key bioactive elements such as polyphenols, caffeine, and bioflavonoids, this investigation has provided insightful insights into how these constituents intricately contribute to heightened sports performance and comprehensive well-being. Notably, the review has underscored the profound impact of caffeine on aspects like alertness, endurance, and recovery, emphasizing the significance of optimal dosages and acknowledging potential challenges associated with higher consumption levels. The antioxidative potency of chlorogenic acids, a critical component, has been emphasized for its role in combatting oxidative stress and inflammation, thereby conferring neuronal safeguarding and facilitating injury convalescence. Furthermore, the psychological ramifications of the sensory encounter, encompassing taste and aroma, have been meticulously explored for their potential influence on the mental facets of sports performance and health. Amid the exposition of coffee's capacity to fortify athletic prowess, it is essential to recognize the imperative of moderation, as the review effectively underscores the

conceivable risks tied to excessive intake. Ultimately, by encapsulating the multifaceted role of coffee in the realm of sports, spanning its bioactive constituents and sensory dimensions, this review effectively establishes its potential to optimize sports performance while contributing holistically to overall well-being. As research in this area deepens, it is poised to reshape the way we think about this common beverage in the context of sports health.

Coffee's role in sports health is gaining traction, and several areas warrant further exploration: (1) Optimal Dosing for Performance and Potential Adaptations: Determining the ideal amount and timing of caffeine intake for different sports categories. Assessing if regular coffee consumption leads to physiological adaptations in athletes over the long term. (2) Post-Exercise Recovery: Investigating coffee's potential in aiding post-exercise muscle recovery and reducing inflammation. (3) The attention could be directed towards identifying compounds capable of mitigating the adverse effects of caffeine, thereby facilitating its utilization for enhancing athletic performance while concurrently minimizing potential detrimental impacts on physiological well-being.

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