УДК [61+615.1] (043.2)
ББК 5+52.81
А 43
ISBN 978-985-21-1864-4

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THE ANTIOXIDANT PROPERTIES OF CAFFEINE: A BIOCHEMICAL PERSPECTIVE

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Caffeine is one of the most widely consumed psychoactive substances globally, primarily found in coffee, tea, and various energy drinks. While its stimulatory effects on the central nervous system are well-studied, recent research has highlighted its potential antioxidant properties. Understanding the biochemical mechanisms behind caffeine's antioxidant activity can provide insights into its broader health implications. Antioxidants are molecules that can neutralize free radicals – unstable molecules that can cause oxidative stress and damage cellular structures, including DNA, proteins, and lipids. By donating electrons to free radicals, antioxidants help mitigate oxidative damage and prevent the development of various diseases, including cancer, cardiovascular diseases, and neurodegenerative disorders.

Caffeine, chemically known as 1,3,7-trimethylxanthine, possesses a structure that allows it to act as a scavenger of free radicals. Several studies have demonstrated the antioxidant activities of caffeine through various mechanisms. Caffeine can directly scavenge reactive oxygen species (ROS) such as hydroxyl radicals (•OH) and superoxide anions (O_2•−) due to its electron-rich structure. This interaction can reduce the availability of these harmful radicals. It may influence the activity of endogenous antioxidant enzymes like superoxide dismutase (SOD) and catalase. By enhancing the body's own antioxidant defence mechanisms, caffeine contributes to a reduced oxidative stress level. Certain metabolite of caffeine can chelate transition metals, such as iron and copper, that catalyze the formation of free radicals. By sequestering these metal ions, caffeine prevents the Fenton reaction, which produces highly reactive hydroxyl radicals.

Caffeine's metabolic pathway include: (1) activation of Nrf2, the master regulator of oxidative stress response, upregulating enzymes like superoxide dismutase (SOD), catalase, and glutathione peroxidase (GPx); (2) adenosine receptor blockade, which indirectly reduces oxidative damage; (3) AMPK activation and phosphodiesterase (PDE) inhibition, both promoting cellular energy homeostasis and redox balance. Caffeine also elevates glutathione (GSH), a key cofactor for GPx, further bolstering antioxidant capacity.

Caffeine is primarily metabolized in the liver into active compounds such as paraxanthine, theobromine, and theophylline, all with antioxidant properties. These metabolites may enhance the protective effects of caffeine, particularly in beverages like coffee and tea, which naturally contain other antioxidants (e.g., polyphenols). Acting synergistically, caffeine and polyphenols may boost overall antioxidant activity more effectively than either compound alone. This interaction could partially explain the observed health benefits associated with moderate coffee and tea consumption, including reduced oxidative stress and inflammation. Additionally, its neuroprotective effects could lower the risk of neurodegenerative disorders like Alzheimer's and Parkinson's.

Caffeine's dual role as both a neurostimulant and antioxidant makes it uniquely valuable for maintaining health and preventing disease. Further research is needed to establish optimal consumption levels and fully understand their long-term impacts. This dual functionality allows us to appreciate caffeine not merely as a stimulant, but as an important compound in combating oxidative stress.