

Beyond the Energy Boost: Molecular Mechanisms and Multisystem Hazards of Energy Drinks

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ABSTRACT

Background: There is a worldwide growing popularity of Energy drinks (EDs). Egyptian studies reported more than one third of adolescents consume energy drinks in Egypt. Many studies reported short and long-term health problems such as cardiovascular events, high blood pressure, gastrointestinal diseases, renal diseases, seizures, insomnia and neuropsychiatric adverse effects.

Ingredients of energy drinks: Besides the high dose of caffeine, energy drinks contain taurine, carbohydrates (sucrose, glucose), acidity regulators (citric acid, sodium citrate), magnesium carbonate, inositol, artificial flavorings, and various B-complex vitamins, including niacinamide, pyridoxine HCl, and vitamin B12. Although energy drinks have some short-term benefits, as EDs can improve the cognitive functions, accelerate physiological responses, increase alertness, improve memory tasks, and minimize the negative effects on the mood and fatigue, they have many adverse effects on health.

Adverse effects of energy drinks: Prolonged or excessive consumption EDs, can lead to significant cytotoxicity through pathways involving oxidative stress, mitochondrial dysfunction, and apoptosis and this can cause cardiovascular, neurological, gastrointestinal, and renal adverse events. Also, EDs interact with several drugs as they increase the effect of paracetamol, lithium, theophylline, and drugs which decrease blood clotting and they reduce the effect of diabetic drugs and methotrexate.

Conclusion: Prolonged or excessive consumption of EDs can cause many hazards on health. Strict regulations of EDs marketing are needed with increasing awareness of their possible hazards on health.

Keywords: energy drink, caffeine, taurine, Red Bull; Monster, adverse effects

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INTRODUCTION

Energy drinks are carbonated, high-caffeine beverages marketed to enhance energy levels [1]. After starting in Asia and Europe in the 1960s, their popularity spread worldwide by the end of the 20th century [2] with market size growth by 9% from 2021 to 2024, reaching 73.99 billion dollars in the year 2024 [3]. Aggressive marketing and widespread retail availability have driven consumption across all demographics, particularly among youth [4]. In Egypt, over one third of adolescents consumed these beverages [4,5]. Despite their popularity, energy drinks carry serious health risks, including cardiovascular events, gastrointestinal diseases, kidney diseases, seizures, insomnia, and manic psychosis [6].

Ingredients of energy drinks

In addition to elevated caffeine concentrations, energy drinks are commonly formulated with taurine,

carbohydrates (sucrose, glucose), acidity regulators (citric acid, sodium citrate), magnesium carbonate, inositol, artificial flavorings, and various B-complex vitamins, including niacinamide, pyridoxine HCl, and vitamin B12 [1]. According to Costantino et al., (2023) [7], Red Bull remains the world's most popular energy drink. It was initially introduced in Austria in 1987 by Chaleo Yoovidhya and Dietrich Mateschitz and expanded to Switzerland in 1994 [8].

Table 1 shows the most popular energy drinks and ingredients per 500 mL [7].

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Table 1: The most popular energy drinks and ingredients per 500 mL (Costantino et al., 2023) ^[7].

Energy Drink	Caffeine (mg)	Sugar (g)	Other Ingredients
Red Bull	160	54	Taurine (2000 mg), gluconolactone (1200 mg), inositol N/S [not specified] and vitamins B3, B5, B6 and B12 N/S
Monster	160	54	Taurine (2000 mg), gluconolactone N/S, carnitine N/S, inositol and guarana N/S, ginseng (400 mg) and vitamins B2, B3, B6 and B12 (40 mg)
Rockstar	160	62	Taurine (2000 mg), carnitine (50 mg), inositol (50 mg) and guarana (50 mg), ginseng (50 mg), ginkgo biloba (300 mg), milk thistle (40 mg) and vitamins B2, B3, B5, B6 and B12 (50 mg)
Mountain Dew	72	61	Carbonated water, high-fructose corn syrup, concentrated orange juice, citric acid, natural flavour, sodium benzoate, caffeine, sodium citrate, gum arabic, erythorbic acid, calcium disodium, yellow 5
Race	160	0	N/S
Sting	290	50	Taurine (148 mg), inositol (21 mg), ginseng (9.7 mg), vitamin B3 (10.2 mg)
Magnus Omniflife	N/S	N/S	N/S
Demon Energy Shot (sold in 60 mL)	1600 (200 mg per 60 mL)	N/S	Taurine (10 g), gluconolactone (N/S), inositol (N/S), B3 (N/S), guarana (60 mg), B5 (N/S), B6 (N/S), B12 (N/S)
Full Throttle	141	57	Taurine (N/S), guarana (N/S), B3 (N/S), B6 (N/S), B8 (N/S), carnitine (N/S)
Lucozade	60.5	23	Carbonated water (N/S), citric acid (N/S), sodium gluconate (N/S), potassium sorbate (N/S), aspartame (N/S), acesulfame K (N/S), flavourings (N/S), sunset yellow (N/S), ponceau 4R (N/S), ascorbic acid (N/S).

For understanding the effect of Eds, it's important to evaluate its ingredients. Depending on the product, energy drinks may contain:

1. Caffeine:

Caffeine acts as a central nervous system stimulant primarily through adenosine receptor antagonism, resulting in enhanced alertness and reduced fatigue. Additionally, it promotes lipolysis, encouraging skeletal muscle to utilize fatty acids over muscle glycogen as an energy substrate, thereby enhancing performance during prolonged exercise ^[9, 10].

While low-to-moderate intake (up to 400 mg daily) is generally considered safe for most healthy adults, excessive consumption, rapid ingestion of concentrated forms, or heightened individual sensitivity can lead to physiological and psychological hazards ^[11].

2. Taurine:

Taurine is a naturally occurring, sulfur-containing amino acid. Physiologically, it enhances skeletal muscle contractility and neurotransmission while mitigating exercise-induced oxidative DNA damage ^[10, 12]. Beyond metabolic function, taurine exhibits antiarrhythmic, positive inotropic, chronotropic, antioxidant and anti-inflammatory properties. It also plays vital roles in cell membrane stabilization, retinal development, and preventing cholestasis ^[9].

However, its therapeutic cytoprotection may be compromised when combined with the high sugar and caffeine concentrations, potentially triggering sympathetic hyperactivation or metabolic confusion ^[7]. Furthermore, Clauson et al., 2008 ^[13] reported that the taurine concentrations in standard commercial energy drinks are too low to exert significant physiological benefit.

3. Sugars:

Sugars provide rapid energy. Consuming them before, during or after prolonged exercise (over an hour) can delay fatigue, protect muscle glycogen reserves, and enhance athletic performance. However, a single 500 ml energy drink delivers roughly 54 grams of sugar—equivalent to 13 teaspoons or a quarter cup. Over time, high intake of simple sugars contributes to obesity and insulin resistance, significantly elevating the risk of diabetes and cardiovascular diseases ^[9, 10, 14].

4. B Vitamins:

These water-soluble vitamins play essential roles in energy metabolism. In energy drinks, they are added to help convert the high sugar content into usable cellular energy ^[9, 10].

- **Thiamine (Vitamin B1):** Facilitates carbohydrate metabolism by driving the oxidative decarboxylation of branched-chain α -keto acid dehydrogenase complexes ^[9].
- **Riboflavin (Vitamin B2):** Supports overall energy pathways involved in metabolism of carbohydrates, lipids, and proteins ^[9].
- **Niacin (Vitamin B3):** Generates nicotinamide adenine dinucleotide (NADH), an essential molecule for cellular energy production as Niacin is a precursor of NAD/NADP and participates in redox metabolism ^[15].
- **Pantothenic Acid (Vitamin B5):** Essential for coenzyme A synthesis, fatty acid oxidation and pyruvate dehydrogenase activity ^[9].
- **Pyridoxine Hydrochloride (Vitamin B6):** has essential role in lipid and glucose metabolism, red blood cell metabolism, nucleic acid (DNA/RNA) synthesis and neurotransmitter synthesis ^[9].
- **Biotin (Vitamin B7):** has essential role in gluconeogenesis and fatty acid oxidation ^[9].
- **Cyanocobalamin (Vitamin B12):** has an important role for red blood cell formation, DNA synthesis and maintaining central nervous system function ^[9].
- 5. **L-Carnitine:** A naturally occurring amino acid synthesized in the liver and kidneys. It facilitates lipid metabolism and alleviates cellular damage, aiding post-exercise muscle recovery ^[9]. Single doses exceeding 2 grams offer no added benefit, as saturation reaches at this dose ^[16].
- 6. **Glucuronolactone:** A naturally synthesized compound in the human body that has a role in initiating the immune system to defend against carcinogens ^[9].
- 7. **Antioxidants:** Essential for post-exercise recovery, these compounds help reduce exercise-induced muscle tissue damage ^[9].
- 8. **Electrolytes (e.g., Sodium and Potassium):** Increasingly added to modern energy drinks to optimize hydration and replenish critical minerals lost through sweat ^[7].

9. Herbal Extracts (e.g., Ginseng and Guarana):

Plant-based additives incorporated into select energy drink formulas to improve overall stimulating effects [7].

Benefits of Energy Drinks:

According to O'Shea et al., (2025) [17], energy drinks (EDs) enhance cognitive function, accelerate physiological responses, increase alertness, improve memory performance, and minimize mood decline and fatigue. However, despite these immediate short-term performance benefits, their consumption is associated with numerous adverse health outcomes [7, 19].

Adverse Effects of Energy Drinks:

Energy drinks (EDs) can cause both acute and chronic adverse effects across multiple systems, including the cardiovascular, neurological, gastrointestinal, and renal systems [6, 7, 19]. Prolonged or excessive ED consumption induces marked cytotoxicity, primarily mediated by oxidative stress, mitochondrial dysfunction, and apoptotic pathways [19, 20].

Oxidative Stress

Oxidative stress arises when the generation of reactive oxygen species (ROS) exceeds the body's antioxidant neutralization capacity [21]. Regular energy drink consumption significantly increases levels of malondialdehyde (MDA); a key marker of lipid peroxidation while concurrently reducing vital antioxidant defenses, including reduced glutathione (GSH), superoxide dismutase (SOD), and catalase (CAT). This depletion weakens cellular defenses, leaving tissues increasingly vulnerable to ROS-mediated damage [20, 22, 23].

Mitochondrial Dysfunction

Chronic or excessive consumption of energy drinks can induce mitochondrial dysfunction, particularly within the cardiovascular and nervous systems [7]. This impairment operates through two primary pathways:

- **ROS-Mediated Damage:** Excessive mitochondrial ROS generation overwhelms cellular antioxidant defenses, causing mitochondrial DNA (mtDNA) damage and reducing membrane potential, ultimately impairing ATP synthesis.
- **Calcium Overload:** Caffeine-induced calcium release from the sarcoplasmic reticulum causes persistent intracellular calcium elevation. This mitochondrial calcium overload disrupts membrane potential and impairs organelle function [7, 24].

Apoptosis (Programmed Cell Death)

Accumulation of severe oxidative stress and mitochondrial damage ultimately forces cells to undergo apoptosis [7].

High caffeine levels drive this process by suppressing the PI3K/Akt/mTOR survival pathway—a central signaling axis regulating cell growth, survival, and metabolism—and by accelerating autophagy, leading to cell death [25]. Furthermore, the high sugar content in energy drinks exacerbates oxidative stress [26], whereas caffeine and guarana directly activate caspase-3, a crucial executioner protein that drives the apoptotic pathway [27].

I. Effect on the Cardiovascular System

Because cardiovascular complications carry life-threatening risks, they remain the most thoroughly investigated adverse effects associated with energy drinks [7]. Even among young, healthy populations, consumption has been associated with serious events such as cardiac arrhythmias, myocardial ischemia, heart attacks, cardiomyopathy, syncope, aortic dissection, cardiac arrest, and sudden cardiac death [19, 28–31]. The pathophysiological mechanisms underlying these cardiac effects are outlined by Costantino et al., (2023) in Fig. 1 [7].

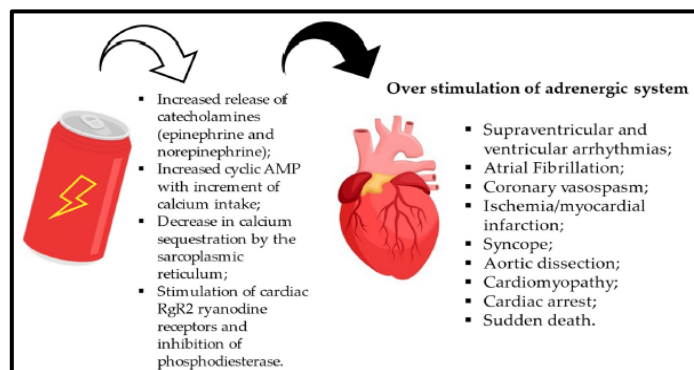


Fig. 1: Pathological effects of energy drinks on cardiac tissue. (Costantino et al., 2023) [7]

Ghamlouch et al., (2025) [18] highlighted striking similarities in how chronic energy drink consumption and cocaine affect the cardiovascular system. Both trigger ion channel blockade, sympathetic overactivation, vasoconstriction, oxidative stress, prothrombotic states, and structural cardiac remodeling. A recent comparative review has highlighted overlapping cardiovascular pathophysiological mechanisms between energy drinks and cocaine (Fig. 2).

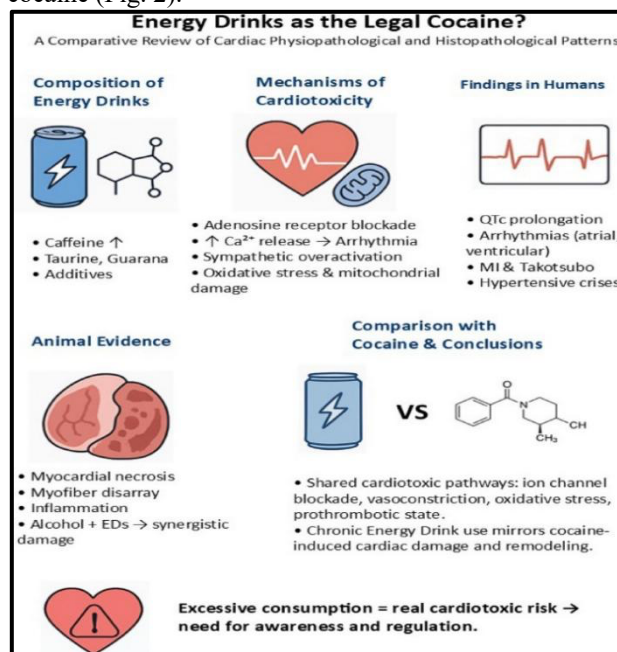


Fig. 2: Comparing the effect of energy drinks and cocaine on cardiovascular physiopathological and histopathological patterns. (Ghamlouch et al., 2025) [18].

II. Effect on the Neurological System

Energy drinks, primarily driven by their high caffeine content, induce adrenergic hyperstimulation by increasing catecholamine release (epinephrine and norepinephrine). This cascade triggers systemic metabolic disturbances, including hyperglycemia, hypokalemia, leukocytosis, and metabolic acidosis, predisposing patients to neurological and psychiatric sequelae such as insomnia, tremors, seizures, cerebral vasculopathy, and manic psychosis [7, 31, 32].

III. Effect on the Gastrointestinal System

Energy drinks contain high concentrations of caffeine, taurine, sugars, and vitamins. Excessive niacin (vitamin B3) intake can induce hepatotoxicity, marked by elevated serum transaminases (ALT/AST) and, rarely, acute liver failure. Caffeine enhances salivary and gastric juice secretion via H_2 receptor activation while reducing lower esophageal sphincter tone, predisposing patients to gastroesophageal reflux. Concurrently, taurine accelerates gastrointestinal motility through action on the myenteric plexus. Collectively, chronic exposure to these compounds has been associated with hypercobalaminemia, atrophic gastritis, pancreatitis, and hepatitis [7].

IV. Effect on the Renal System

Experimental studies suggest that long-term consumption, high-dose of energy drinks over activates RAAS (renin-angiotensin-aldosterone system), leading to increasing the expression of renin, angiotensin-converting enzyme (ACE), and angiotensin II. This cascade elevates systemic blood pressure and increases microvascular renal strain, ultimately impairing renal function, as evidenced by elevated serum creatinine, urea, and uric acid levels [33]. Notably, cases of acute kidney injury (AKI) secondary to acute tubular necrosis have been documented in healthy young adults following prolonged, high-volume ingestion [34].

Excessive intake of energy drink alters renal hemodynamics and metabolic homeostasis, increasing glomerular filtration while decreasing tubular sodium reabsorption. Coupled with systemic hyperglycemia, hypokalemia, and metabolic

acidosis, these alterations precipitate natriuresis, severe dehydration, acute tubular necrosis, AKI, and coma [7] (Fig. 3).

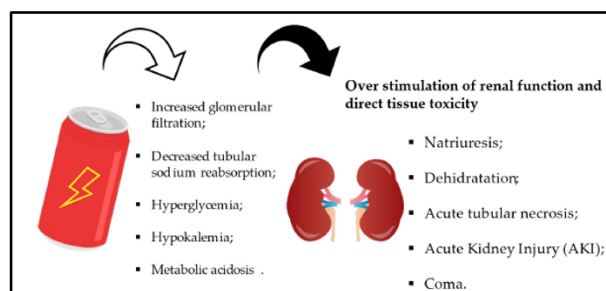


Fig. 3: Pathological effects of energy drinks on renal tissue. (Costantino et al., 2023) [7].

emphasize the clinical necessity of routinely screening for energy drink consumption during history taking to prevent severe or life-threatening drug-drug interactions.

Conclusion

Although individual ingredients of energy drinks appear to be safe, prolonged or excessive consumption can cause many hazards on health. Strict regulations of EDs marketing are needed with increasing awareness of their possible hazards on health.

Declaration of conflicting interest

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