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Review

Advancements in Chemical Additives for Fuels and Food Engineering: A Technical Review

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Abstract: Chemical additives are widely used in modern industries, especially in fuel manufacturing and food processing, playing essential roles in performance enhancement, preservation, stabilization, and safety. In the fuel industry, additives are used to improve combustion efficiency, reduce emissions, and stabilize fuel in varying environments. In the food industry, additives are used to preserve quality, improve sensory attributes, and support food safety. Advancements in materials science, synthetic chemistry, and artificial intelligence (AI)-assisted design lead to the development of efficient and environment-friendly additives. This review provides an overview of chemical additives used in fuels and food, their functions, synthesis, sustainability concerns, and future trends with an emphasis on nanotechnology-based additives, biodegradable agents, and the integration of machine learning models in additive development.

Keywords: Chemical additive, Fuel, Food engineering, Food process, Additive development

1. Introduction

Chemical additives are added in trace amounts to significantly improve the function, appearance, stability, or performance of various products. In fuel manufacturing, chemical additives are used to enhance combustion properties, stabilization, lubrication, flame control, storage, transport, and corrosion and deposit inhibition, while food additives are used to extend shelf life, enrich sensory attributes, and meet nutritional or safety requirements [1,2]. In both industries, chemical additives have been developed and improved over the past decades, affected by consumer demand, technological advancement, and regulations. Recently, bio-based and multifunctional additives have been introduced amid the increasing emphasis on green chemistry and sustainability. Concerns over chemical safety and environmental protection necessitate rigorous testing and life-cycle assessments of chemical additives used in the industry. This review aims to examine how chemical additives are used in fuel and food systems, focusing on their composition, function, synthesis, challenges, and future development. Especially, how advanced technologies, including artificial intelligence and nanotechnology, are used in the chemical engineering processes in the fuel and food engineering is also explored.

2. Chemicals in Fuel Systems

2.1. Additives in Petroleum-Based Fuels

Petroleum-derived fuels, gasoline and diesel, are composed of hydrocarbon mixtures whose combustion and physical characteristics are inherently inconsistent and environmentally harmful. Chemical additives are used to solve such problems. For instance, detergents are used to prevent deposit formation in fuel injectors and intake valves to maintain engine efficiency, while corrosion inhibitors are used to protect fuel system components. Antioxidants prevent gum formation during storage, and anti-knock agents, such as tetraethyl lead (historically) and modern replacements such as methylcyclopentadienyl manganese tricarbonyl (MMT), increase the octane rating of gasoline [3]. Oxygenates such as methyl tertiary-butyl ether (MTBE) and ethanol facilitate complete combustion by increasing oxygen availability in the air-fuel mixture and reducing carbon monoxide emissions [4]. However, additives such as MTBE can contaminate groundwater, leading to an increased use of ethanol and other bio-based oxygenates. The concentrations of additives in fuel normally range from 0.01 to 0.1% in volume, yet their effectiveness on fuel behavior and emission reduction is considerable. The effect of sulfur is also suppressed by using chemical additives, as sulfur interferes with catalytic converters and causes acid rain [5].

2.2. Additives in Hydrogen Fuel Systems

Hydrogen has been used as a fuel for vehicles due to its clean properties, but it presents several challenges. Although the combustion of pure hydrogen produces only water as a by-product, the hydrogen fuel cell has low energy density, high diffusivity, and embrittles storage tanks and pipelines made of metals. Chemical additives for hydrogen fuel systems are used to stabilize storage media (e.g., metal hydrides), enhance leak detection through odorization, and reduce material degradation [6,7]. Borohydrides, amine-boranes, and metal-organic frameworks (MOFs) have been researched for the carriers and stabilizers of hydrogen. These compounds absorb and release hydrogen under mild conditions, and enable safe and more efficient storage. Hydrogen additive development, though still in its early stages compared with petroleum-based additives, is advancing rapidly, driven by innovation and increasing demand for cleaner energy solutions.

2.3. Environmental and Performance

Environmental regulations have been formulated for controlling cleaner-burning fuels and prompting additive manufacturers to balance effectiveness with environmental impact. Especially, the use of detergents, lubricity enhancers, and cold-flow improvers is strictly regulated under low-sulfur regulations without compromising engine performance or emissions control systems [5]. Recently, chemical additives, which are biodegradable and contain low-toxicity compounds, have been increasingly used. However, the high cost and low scalability of such environment-friendly additives remain challenges to their widespread adoption.

3. Chemicals in Food Engineering

3.1. Preservatives and Antimicrobials

Food preservatives are used to minimize food spoilage and extend the shelf life by inhibiting microbial growth and oxidative deterioration. Common preservatives include sodium benzoate, potassium sorbate, and nitrites, which disrupt microbial metabolism or cell membrane integrity to effectively delay spoilage [8]. Natural preservatives, such as essential oils, plant polyphenols, and organic acids, have been widely used due to consumer demand for environment-friendly products. However, natural compounds have limited antimicrobial activities and higher volatility, necessitating advanced delivery systems such as nanoencapsulation for effective functions [9].

3.2. Flavor and Texture Enhancers

Flavor enhancers such as monosodium glutamate (MSG) amplify umami taste perception, while texture enhancers, such as lecithin and xanthan gum, enable the consistency, emulsification, and stability of foods [10]. These additives interact with food proteins, polysaccharides, and fats at the molecular level to enhance desired rheological and sensory properties. In processed food systems, precise control of the concentration and interaction of these additives is essential to maintain product acceptability and compliance with food safety regulations.

3.3. Colorants and Nutritional Additives

Colorants are mainly added for aesthetic, psychological, and marketing purposes. Colorants are widely used in the food industry to enhance the appearance, color stability, and consistency of products. However, disadvantages in using colorants also exist, including health concerns and environmental impact [11–13]. Natural colorants, including anthocyanins, carotenoids, and chlorophylls, are used as alternatives to synthetic colorants owing to their reduced stability and color consistency [14]. Nutritional additives, including vitamin D, iron, and folic acid, are widely used to address micronutrient deficiencies. The effectiveness of such fortifiers depends heavily on their bioavailability and resistance to degradation during food processing.

3.4 Regulatory and Safety Frameworks

All food additives must comply with regional safety assessments. Regulatory authorities such as the Food and Drug Administration in the United States of America and the European Food Safety Authority evaluate toxicological data, establish acceptable daily intake (ADI) levels, and monitor cumulative exposure [15]. However, safety assessments often require several years, as carcinogenicity, reproductive toxicity, mutagenicity, and other tests must be performed.

In Japan, the emphasis on clean-label products has led to the development of plant-based natural preservatives such as fermented soybean extract [13]. European nations are adopting stricter regulations on artificial dyes and synthetic flavorings due to consumer advocacy [16]. Brazil has promoted locally sourced antioxidants from Amazonian fruits like açaí and guarana to preserve juices and frozen foods [17].

4. Chemical Engineering of Additives

4.1. Synthesis Pathways

Fuel and food additives are synthesized using organic synthesis (esters, ethers, and antioxidants), polymer chemistry (anti-static and viscosity-modifying additives), and enzymatic processes to produce food-grade emulsifiers and natural flavors [18]. Chemical additives for fuel and food are extensively designed through synthetic procedures. Additives to petroleum fuel, such as polyetheramines, are synthesized via polymerization followed by functional group modification [19]. Food additives such as ascorbic acid are produced through multistep fermentation and hydrogenation processes. The manufacturing methods of chemical additives need to increase yield, selectivity, solvent recovery, and minimize waste. Flow chemistry and biocatalysis are increasingly adopted to improve the sustainability of manufacturing processes and reduce costs. Increasing concern over environmental toxicity has led to the adoption of green synthesis methods, including enzyme-catalyzed synthesis of food emulsifiers, biodegradable fuel additives such as polyglycerol esters, and plant-extracted antioxidants in biodiesel represent sustainable alternatives [20].

4.2. Catalysis in Additive Production

Catalysts are indispensable in manufacturing chemical additives. Heterogeneous catalysts, such as alumina, zeolites, or supported metal complexes, are used in high-temperature fuel additive synthesis. In manufacturing food additives, enzymatic catalyses are widely used for selective reactions under mild conditions [21]. Catalyst influences the product purity, reaction speed, and energy efficiency of the produced chemical additives. Catalyst recyclability and nanostructuring have contributed to the development of chemical additives.

4.3. Nanotechnology and Encapsulation

Nano- and micro-encapsulation techniques are widely used to enhance the delivery, stability, and control of chemical additive manufacturing. In food processing, liposomes, micelles, and polysaccharides are used to improve the stability of sensitive compounds such as antioxidants and probiotics [9]. In fuel manufacturing, nano-additives such as ceria or alumina nanoparticles are used to enhance combustion, reduce friction, and act as deposit inhibitors. Microencapsulation enables dual or timed-release functionality, which has been introduced in pharmaceuticals and functional food processing and manufacturing.

5. Future Development and Trends

5.1. Biobased and Biodegradable Additives

Due to an increasing awareness of environmental problems, bio-based additives are increasingly used. Essential oils, phenolics, and terpenes from plants have been researched and used in developing and manufacturing chemical additives owing to antimicrobial and fuel-enhancing properties [22]. However, the bio-based additive has challenges such as standardization, volatility control, and cost-effective extraction. Chemical additives must be validated for biodegradability, so novel biodegradable polymers and esters have been actively developed to enhance the functionality of chemical additives. Safety assessment of additives includes acute and chronic toxicity, carcinogenicity, reproductive health effects, and environmental impact. Fuel additives must comply with registration, evaluation, authorisation, and restriction of chemicals (REACH) in the EU and EPA standards in the U.S. [23]. Food additives are tested through animal studies, no observed adverse effect level (NOAEL), and acceptable daily intake (ADI) determinations [24].

5.2. Multifunctional Additives

Multifunctional additives play multiple roles as antioxidants and corrosion inhibitors in fuel, and as antimicrobial agents and flavor enhancers in food [25]. Multifunctional additives are used to reduce formulation complexity, ingredient interaction issues, and regulatory documentation. Tailoring molecular structures for multifunctionality is an important research topic, facilitated by combinatorial chemistry and molecular modeling [26].

5.3. Computational and Artificial Intelligence (AI)-Assisted Design

AI and machine learning are used to find and develop new chemical additives. Algorithms trained on physicochemical datasets are used to predict and validate additive behavior, solubility, and reactivity with high accuracy, which reduces experimental burden and accelerates development processes. Such methods are especially useful in designing chemical additives for hydrogen storage or food fortification, where conventional trial-and-error approaches are inefficient. Machine learning algorithms help predict the stability and sensory effects of food additives [27]. Computational fluid dynamics (CFD) and quantum chemical modeling assist in fuel additive behavior analysis under combustion conditions [28]. Nanoparticles, such as cerium oxide and titanium dioxide, have been used as fuel combustion enhancers and emission reducers [29]. In food, nanoencapsulation improves bioavailability of additives like omega-3s and curcumin [30]. However, challenges remain regarding regulation and consumer acceptance.

5.4 Circular Chemistry and Sustainability

Sustainable additive design is increasingly emphasized in full life-cycle assessments (LCA), which involves raw material sourcing, production, use, and degradation. Circular economy encourages the use of industrial byproducts, biodegradable inputs, and closed-loop synthesis pathways [31]. Legislative pressure, such as the EU's Green Deal and EPA frameworks, leads industries to be more transparent and to adopt ecologically sound practices.

6. Conclusion

Additives play an essential role in ensuring the safety, performance, and sustainability of fuels and foods. Despite significant differences in their functions, challenges such as environmental impact, regulatory compliance also remain, and innovation in synthesis and delivery is still required. Advances in catalysis, nanotechnology, and AI-driven design have enabled next-generation additives that are more efficient, multifunctional, and environmentally benign than existing additives. As industries are adopting decarbonization and health-conscious production strategies, chemical additives play a critical role in applied functional materials research.

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