



THE ROLE OF CARBOXYLIC ACIDS IN GREEN CHEMISTRY AND SUSTAINABLE DEVELOPMENT

Qo'ldoshev Shavkat To'rayevich

Chemistry Teacher,

Technical School №2, Karshi District, Uzbekistan

<https://doi.org/10.5281/zenodo.20568825>

Abstract

The rapid development of industry and technology has significantly improved human life; however, it has also led to serious environmental challenges, including pollution, excessive consumption of natural resources, and the accumulation of non-biodegradable waste. In response to these issues, the concept of green chemistry has emerged as a sustainable approach aimed at reducing the environmental impact of chemical processes. Carboxylic acids, an important class of organic compounds, play a significant role in the development of environmentally friendly technologies. These compounds are widely used in food production, pharmaceuticals, agriculture, polymer synthesis, and biodegradable materials. This article discusses the structure, properties, classification, and applications of carboxylic acids, with particular emphasis on their contribution to green chemistry and sustainable development.

Keywords: *Carboxylic acids, green chemistry, sustainability, biodegradable polymers, lactic acid, citric acid, environmental protection.*

Introduction

Environmental protection and sustainable industrial development have become global priorities in the twenty-first century. Scientific research increasingly focuses on developing chemical processes that minimize waste production, reduce toxicity, and utilize renewable resources. Green chemistry, first introduced in the 1990s, seeks to design products and processes that eliminate or reduce the generation of hazardous substances.

Among the various compounds utilized in green chemistry, carboxylic acids occupy a prominent position due to their versatility and environmental compatibility. Carboxylic acids are organic compounds containing the carboxyl functional group (-COOH), which consists of both a carbonyl group (C=O) and a hydroxyl group (-OH). These compounds occur naturally in plants, animals, and microorganisms and are involved in numerous biological and industrial processes.

Common examples include formic acid, acetic acid, lactic acid, citric acid, oxalic acid, and benzoic acid. Their diverse chemical properties make them valuable raw materials in the production of pharmaceuticals, food additives,

biodegradable plastics, and agricultural products. As industries strive to reduce their ecological footprint, the importance of carboxylic acids continues to grow.

Chemical Structure and Properties of Carboxylic Acids

The general formula of monocarboxylic acids is R-COOH, where R represents an alkyl or aryl group. The carboxyl group is responsible for the acidic behavior of these compounds. Due to resonance stabilization, carboxylic acids readily donate a proton (H⁺), making them weak acids.

Several physical and chemical properties distinguish carboxylic acids from other organic compounds:

Physical Properties

Carboxylic acids possess relatively high boiling points because they form hydrogen bonds between molecules. Lower members of the series, such as formic acid and acetic acid, are colorless liquids with strong odors, while higher molecular-weight acids are often solids.

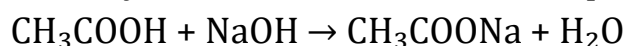
The solubility of carboxylic acids in water depends on the length of the carbon chain. Short-chain acids dissolve readily due to hydrogen bonding with water molecules, whereas long-chain acids become increasingly insoluble.

Chemical Properties

Carboxylic acids participate in numerous chemical reactions:

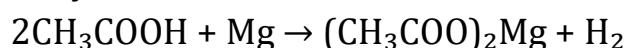
1. Neutralization Reaction

Carboxylic acids react with bases to produce salts and water:



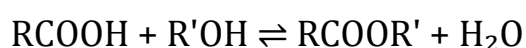
2. Reaction with Metals

They react with active metals to release hydrogen gas:



3. Esterification

One of the most important reactions involving carboxylic acids is esterification. In the presence of an acid catalyst, they react with alcohols to form esters and water.



Esters produced through this process are widely used in perfumes, flavorings, cosmetics, and pharmaceuticals.

Classification of Carboxylic Acids

Carboxylic acids can be classified according to the number of carboxyl groups present in their molecules.

Monocarboxylic Acids

These acids contain one carboxyl group. Examples include:

- Formic acid (HCOOH)
- Acetic acid (CH_3COOH)
- Benzoic acid ($\text{C}_6\text{H}_5\text{COOH}$)

Dicarboxylic Acids

These compounds contain two carboxyl groups.

Examples:

- Oxalic acid
- Malonic acid
- Succinic acid

Dicarboxylic acids are widely used in polymer production and industrial synthesis.

Polycarboxylic Acids

These acids possess three or more carboxyl groups.

Examples:

- Citric acid
- Tartaric acid

Such compounds are important in food preservation and biological metabolism.

Industrial Applications of Carboxylic Acids

Food Industry

Carboxylic acids play a crucial role in food preservation and flavor enhancement. Citric acid is widely used as an acidity regulator and antioxidant. Acetic acid is the principal component of vinegar and acts as a natural preservative.

Benzoic acid and sorbic acid are commonly employed to prevent microbial growth in food products, thereby extending shelf life.

Pharmaceutical Industry

Many medicinal compounds are synthesized from carboxylic acids. Salicylic acid serves as a precursor for aspirin, one of the most widely used drugs worldwide.

Carboxylic acid derivatives are also found in antibiotics, anti-inflammatory drugs, and vitamins. Their chemical reactivity allows scientists to design molecules with specific therapeutic effects.

Textile and Cosmetic Industries

In textile manufacturing, carboxylic acids are used in dyeing and finishing processes. Cosmetic products frequently contain citric acid, lactic acid, and glycolic acid for skin care purposes.

Alpha-hydroxy acids (AHAs), a subgroup of carboxylic acids, are widely utilized in anti-aging creams and chemical peeling treatments because they promote skin renewal and improve texture.

Carboxylic Acids in Green Chemistry

The growing concern over environmental degradation has encouraged researchers to develop sustainable alternatives to conventional chemical products. Carboxylic acids contribute significantly to green chemistry principles through several mechanisms.

Production of Biodegradable Plastics

One of the most promising applications of carboxylic acids is the production of biodegradable polymers. Lactic acid, obtained through fermentation of renewable resources such as corn starch and sugarcane, serves as the monomer for polylactic acid (PLA).

PLA possesses several environmental advantages:

- Derived from renewable resources.
- Biodegradable under industrial composting conditions.
- Reduces dependence on petroleum-based plastics.
- Produces fewer greenhouse gas emissions during manufacturing.

As governments worldwide implement regulations to reduce plastic pollution, the demand for PLA-based products continues to increase.

Green Solvents and Sustainable Processes

Traditional organic solvents often pose environmental and health risks due to their toxicity and volatility. Researchers have developed environmentally friendly solvents based on carboxylic acid derivatives. These solvents reduce hazardous emissions and improve workplace safety.

Carbon Capture and Resource Efficiency

Recent studies indicate that certain carboxylic acid-based systems can facilitate carbon dioxide capture and utilization. Such technologies may help reduce atmospheric CO₂ levels and mitigate climate change.

Moreover, carboxylic acids are often synthesized from biomass, supporting the transition toward a circular economy in which renewable resources replace fossil fuels.

Agricultural Applications

Agriculture increasingly relies on sustainable practices to ensure food security while protecting natural ecosystems.

Carboxylic acids contribute to agriculture in several ways:

Soil Improvement



Organic acids improve nutrient availability by chelating metal ions and enhancing mineral absorption by plants.

Silage Production

Lactic acid bacteria ferment carbohydrates in animal feed, producing lactic acid that preserves silage and improves livestock nutrition.

Plant Growth Promotion

Certain carboxylic acids stimulate root development and increase plant resistance to environmental stress. As a result, crop productivity can be enhanced while reducing dependence on synthetic chemicals.

Environmental Benefits and Future Perspectives

The future significance of carboxylic acids extends beyond their current applications. Ongoing research focuses on developing innovative materials and technologies based on these compounds.

Future directions include:

- Advanced biodegradable polymers.
- Sustainable packaging materials.
- Carbon-neutral industrial processes.
- Green catalysts for chemical synthesis.
- Renewable biofuels and energy-storage materials.

Scientists are also exploring microbial and enzymatic methods for producing carboxylic acids more efficiently and sustainably. Such approaches align with global efforts to reduce greenhouse gas emissions and achieve sustainable development goals.

As environmental regulations become stricter and public awareness increases, industries are expected to adopt carboxylic acid-based technologies more extensively.

Conclusion

Carboxylic acids represent one of the most versatile and valuable classes of organic compounds. Their unique chemical properties and broad range of applications make them indispensable in food production, pharmaceuticals, agriculture, cosmetics, and polymer industries. More importantly, their contribution to green chemistry and sustainable development highlights their relevance in addressing modern environmental challenges.

The use of renewable resources for the production of carboxylic acids, together with their role in biodegradable materials and environmentally friendly technologies, demonstrates their potential to support a more sustainable future. Continued research and innovation in this field will undoubtedly expand their



applications and strengthen their role in achieving environmentally responsible industrial development..

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