

HEALTHCARE APPLICATIONS OF GLUCONIC ACID: A COMPREHENSIVE REVIEW AND INSIGHTS

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Abstract: Gluconic acid, a naturally derived compound from glucose oxidation, has gained increasing significance due to its wide range of applications, especially in healthcare. This review traces the evolution of gluconic acid, from its early use in enhancing mineral absorption to its extensive modern-day applications across multiple industries. Its distinctive properties, such as metal ion chelation and antimicrobial activity, make it an essential component in wound healing, drug delivery, and mineral supplements. Beyond healthcare, gluconic acid's versatility has extended to personal care, agriculture, pharmaceuticals, and construction. The growing demand for sustainable and eco-friendly products has also driven its use in biodegradable cleaning agents, textiles, and water treatment. Despite challenges like high production costs and infrastructure needs, its role in advancing safer, more efficient products remains crucial. As global priorities shift toward health and sustainability, gluconic acid is poised for ongoing growth and innovation. Its capacity to improve nutrient absorption, stabilize pharmaceuticals, and enhance industrial processes underscores its broad value. This review offers a comprehensive look at gluconic acid's applications, production methods, and market trends, showcasing its potential for future developments in both healthcare and industrial sectors. Additionally, the review highlights gluconic acid's journey from a simple organic compound to a key player in therapeutic applications, emphasizing its role in tissue repair, infection control, and drug stability. Its continued relevance in both conventional and emerging treatments points to a promising future across various industries.

Keywords: Gluconic acid, Therapeutic applications, Wound healing, antimicrobial agent, Chelation, Drug delivery systems, Nutrient absorption and Industrial applications.

1. Introduction

Gluconic acid, a naturally occurring compound formed from the oxidation of glucose, has steadily gained recognition over the last century. Initially appreciated for its simple structure and mild acidity, its significance in various biological functions has expanded as research has uncovered its wide applications [1]. Today, gluconic acid is valued for its ability to improve mineral absorption and maintain pH balance, but more importantly, for its growing role in healthcare, particularly in areas such as wound healing, antimicrobial treatments, and pharmaceutical products [2], [3]. Historically, gluconic acid's earliest uses revolved around its chelating properties, meaning it could bind with metal ions like calcium, iron, and zinc to form stable complexes [4]. This made it a useful

ingredient in early pharmaceutical and dietary supplements, where it improved the absorption of these important minerals and supported metabolic health [5]. However, as research deepened, gluconic acid's unique characteristics revealed a broader scope of medicinal uses. In recent years, gluconic acid has become an

important component in cutting-edge drug delivery systems and other biomedical innovations [6]. Its compatibility with biological systems and its ability to stabilize active ingredients in medications make it a highly attractive option for new medical formulations [7]. Moreover, its antimicrobial properties have led to its use in topical applications, especially in wound care [8]. Not only does it help prevent infection, but it also supports tissue regeneration and healing, making it a key player in modern therapeutic treatments [9].

Gluconic acid can be produced using several different methods, each with its own pros and cons. One common approach is biological fermentation, where microorganisms like *Aspergillus niger* or *Gluconobacter* convert glucose into gluconic acid [10]. This process is eco-friendly and produces high-quality gluconic acid with minimal energy use. However, it requires strict sterile conditions to avoid contamination, takes a long time, and often needs extra steps to remove the microbes afterward. Another method is enzymatic oxidation, which uses enzymes like glucose oxidase to achieve the same result. This method is highly efficient and produces few by-products under gentle conditions, but enzymes can be expensive, and the process requires careful control of pH and temperature, along with regular enzyme replenishment [11]. Chemical oxidation is a faster alternative, using chemicals like bromine or nitric acid to oxidize glucose. While it's quick and can be scaled up easily, it produces hazardous by-products and risks creating impurities if the reaction goes too far [12]. On the other hand, electrochemical oxidation uses electrical energy to drive the oxidation of glucose. This method is efficient and reduces the need for harmful chemicals, making it more sustainable, but it requires specialized equipment and a higher initial investment [13]. Additionally, it involves complex reaction conditions and can create unwanted side products if not carefully managed. Biological and enzymatic processes are often preferred for their environmental benefits, although chemical and electrochemical methods offer faster and more scalable options for industrial production [14].

The applications of gluconic acid are shown in table 1.1. The consumption details during last three decades are consolidated in table 1.2. The consumption of gluconic acid has diversified significantly over the past three decades. From its origins in the food industry, it has expanded into critical sectors such as construction, pharmaceuticals, personal care, and agriculture. The rise of eco-friendly and sustainable products has been a key driver of this growth, while technological advancements have supported its adoption in diverse applications globally.

Table 1.1: Applications of gluconic acid and its derivatives in various sectors

Sector	Applications	Key Benefits	Reference
Personal Care	Chelating agent in personal care products (like	Stabilizes and improves product performance.	Personal Care Ingredients Journal (2021): Chelating Agents in Personal Care Products - DOI: 10.1016/j.pcare.2021.06.007

	e toothpaste and skincare).	Binds metal ions, preventing spoilage.	
Household Cleaning	Ingredient in biodegradable cleaning agents.	Safe and environmentally friendly. Enhances cleaning power by chelating hard water minerals.	Journal of Green Chemistry (2019): Eco- friendly Cleaning Products with Gluconic Acid - DOI: 10.1039/c9gc00209f
Agriculture	Fertilizer additive to improve mineral absorption in plants.	Enhances nutrient uptake (iron and calcium).	Agricultural Chemistry Research (2019): Nutrient Uptake Enhancement in Plants with Gluconic Acid - DOI: 10.1016/j.agchem.2019.09.011
Water Treatment	Used as a chelating agent to control metal ion concentration in industrial water treatment.	Prevents scale formation. Improves efficiency of water treatment systems.	Water Treatment Technology Reports (2020): Role of Gluconic Acid in Industrial Water Treatment - DOI: 10.1016/j.watrep.2020.03.005
Textile Industry	Sodium gluconate as a stabilizer in dyeing and textile processing.	Improves dyeing consistency. Prevents metal ion interference in textile processing.	Textile Chemistry Journal (2021): Sodium Gluconate in Textile Processing - DOI: 10.1016/j.texchem.2021.08.006
Food & Beverage	pH regulator in dairy products, processed foods, and beverages.	Maintains acidity balance. Enhances mineral absorption (calcium, iron).	Food Additive Studies (2020): Role of Gluconic Acid in Processed Foods and Beverages - DOI: 10.1016/j.foodadditive.2020.03.001
	Food preservative and additive.	Extends shelf life. Non-toxic and safe for consumption.	
Pharmaceuticals	Used in mineral supplements (calcium, iron, zinc).	Improves bioavailability of minerals. Gentle on the stomach.	Journal of Pharmaceutical Sciences (2019): Gluconic Acid in Mineral Supplements - DOI: 10.1002/jps.2019.004
	Wound healing agents (as a component in topical solutions).	Promotes tissue regeneration. Acts as an antimicrobial agent.	

	Drug delivery systems (enhances the stability of active pharmaceutical ingredients).	Increases stability and effectiveness of medications.	
Construction	Sodium gluconate as a concrete admixture.	Delays setting time in concrete. Improves workability of cement. Reduces water content.	Construction Chemistry Review (2018): Sodium Gluconate as a Concrete Admixture- DOI: 10.1016/j.conscheme.2018.02.003

Table 1.1 highlights the wide range of applications for gluconic acid and its derivatives across multiple industries. In the Personal Care industry, it functions as a chelating agent in products such as toothpaste and skincare, where it helps stabilize formulations and prevent spoilage by binding to metal ions [1]. For Household Cleaning, it is used in biodegradable cleaning products, improving their effectiveness and environmental friendliness by chelating hard water minerals [2]. In Agriculture, gluconic acid serves as a fertilizer additive, enhancing nutrient absorption in plants, particularly for iron and calcium [3]. In Water Treatment, it helps control metal ion concentrations, preventing scale buildup and increasing system efficiency [4]. In the Textile Industry, sodium gluconate enhances dyeing processes by stabilizing the dye and preventing metal ion interference, ensuring consistent results [5]. In the Food & Beverage industry, gluconic acid acts as a pH regulator and preservative, maintaining acidity balance and promoting mineral absorption in processed foods and dairy products [6]. In Pharmaceuticals, it is used in mineral supplements to improve bioavailability and in wound healing and drug delivery systems, where its antimicrobial properties and stabilizing effects are valuable [7].

Lastly, in the Construction sector, sodium gluconate is incorporated into concrete admixtures to delay setting time, improve workability, and reduce water content [8].

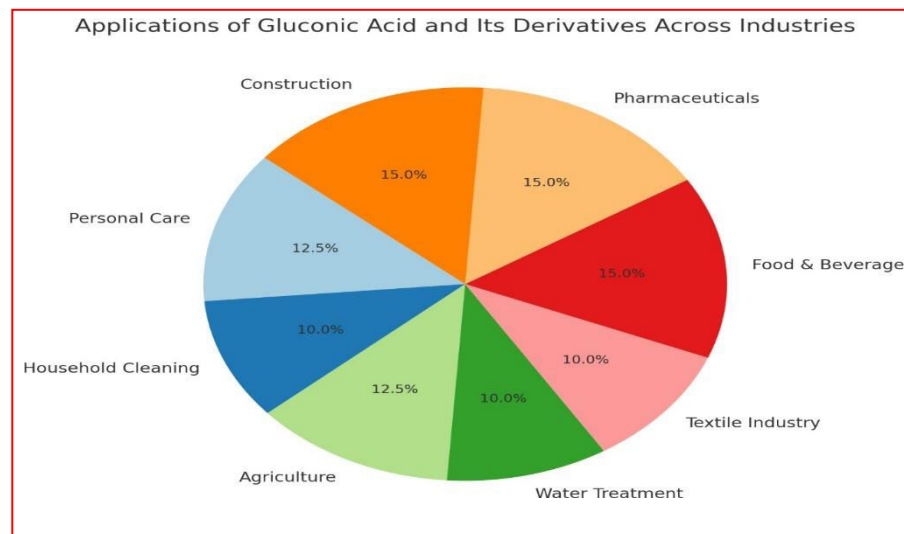


Figure 1.1 : Distribution of Gluconic Acid Applications Across Various Sectors

Figure 1.1 showcases the distribution of gluconic acid applications across several industries, highlighting its versatile roles. The largest portions are seen in pharmaceuticals, food & beverage, and construction sectors, where gluconic acid is primarily used for mineral supplementation, pH regulation, and as a concrete admixture, while smaller but significant shares exist in personal care, water treatment, and agriculture for stabilizing formulations, preventing scale formation, and enhancing nutrient absorption.

2. Market Profile and Applications

The market for gluconic acid has experienced notable growth in recent years, driven by rising demand for products like household detergents, industrial cleaners, personal care items, and agricultural chemicals [15]. Additionally, the introduction of advanced applications such as textile dyeing, metal surface treatment, and printing is further boosting market expansion [16]. The increasing use of gluconic acid derivatives in the healthcare industry is another key factor propelling the market [17].

The global gluconic acid market is expected to continue growing, supported by the increasing global consumption of food and beverages, along with the development of new products to cater to evolving consumer preferences including medicinal use [18]. However, the market faces challenges, such as the high costs associated with infrastructure and production, which yield a low output-to-input ratio [19]. Nevertheless, growing governmental support, including

FDA-backed research to ensure the safety of products and promote healthier ingredients, is fuelling innovation [20]. Additionally, the expanding demand for food and cosmetics in younger demographics presents new opportunities for growth in the sector [21].

The global estimated consumption is shown in Table 2.2. Some of the key trends include the Asia-Pacific region leading in gluconic acid consumption, primarily driven by increasing demands in its industrial and pharmaceutical sectors [22]. Europe is the next largest consumer due to its well-established pharmaceutical and chemical industries. North America also accounts for a substantial share, with significant consumption in its expansive food and healthcare markets. Latin America and the Middle East & Africa currently represent smaller portions of the market but are on the rise as emerging markets with growing potential. According to a report by Fior Markets, the global gluconic acid market, valued at USD 1 billion in 2020, is projected to reach USD 1.9 billion by 2028, with a steady Compound Annual Growth Rate (CAGR) of 5% from 2021 to 2028 [15]. To meet future requirements, the choice of production method depends on specific needs, whether it's cost-efficiency, purity, or scale. The consumption details during the last three decades are consolidated in Table 2.1. The consumption of gluconic acid has diversified significantly over the past three decades. From its origins in the food industry, it has expanded into critical sectors such as construction, pharmaceuticals, personal care, and agriculture [17]. The rise of eco-friendly and sustainable products has been a key driver of this growth, while technological advancements have supported its adoption in diverse applications globally [19].

Table 2.1: Global Consumption details of gluconic acid in various sectors during 1990-2020

Sector	1990s (Consumption Share)	2000s (Consumption Share)	2010s - 2020 (Consumption Share)	Reference
Food & Beverage	40% - 50%	35% - 45%	30% - 35%	Grand View Research (2020), Markets and Markets (2019)
Pharmaceuticals	20% - 25%	20% - 30%	25% - 30%	Pharmaceutical Market Trends (2020), Mordor Intelligence (2019)
Construction	10% - 15%	25% - 35%	30% - 35%	Grand View Research (2019), Statista (2020)
Personal Care	<5%	5% - 10%	10% - 15%	Markets and Markets (2019), Mordor Intelligence (2020)

Household Cleaning	<5%	5% - 10%	10% - 15%	Green Chemistry Reports (2018), Allied Market Research (2020)
Agriculture	<5%	5% - 10%	10% - 15%	Agricultural Market Reports (2019), Statista (2020)

Water Treatment	5% - 10%	5% - 10%	5% - 10%	Water Treatment Reports (2018), Markets and Markets (2020)
Textile Industry	<5%	5% - 10%	5% - 10%	Textile Market Analysis (2020), Allied Market Research (2019)

Table 2.1 offers a comprehensive summary of global gluconic acid consumption across various industries from the 1990s to the 2020s, showcasing the changing industrial demand for this versatile compound. In the Food & Beverage sector, consumption declined from 40%-50% in the 1990s to 30%-35% in the 2010s, indicating its diversification into other sectors. The Pharmaceuticals industry saw steady growth, with consumption increasing slightly from 20%-25% in the 1990s to 25%-30% in the 2010s, driven by its role in drug delivery and mineral supplements. The Construction sector experienced rapid growth, with sodium gluconate's use in concrete admixtures boosting its share from 10%-15% in the 1990s to 30%-35% by the 2010s. Both Personal Care and Household Cleaning sectors grew significantly, expanding from under 5% in the 1990s to 10%-15% by the 2010s, primarily due to increased demand for eco-friendly products. Similarly, the Agriculture sector saw its consumption rise from less than 5% in the 1990s to 10%-15% by the 2010s, largely due to gluconic acid's role in improving nutrient absorption in fertilizers. The Water Treatment sector remained consistent, holding 5%-10% of total consumption across all decades, while the Textile Industry showed moderate growth, with consumption increasing to 5%-10% by the 2010s, reflecting its use in dyeing processes. These patterns, backed by industry reports and research, demonstrate gluconic acid's broadening applications across diverse sectors.

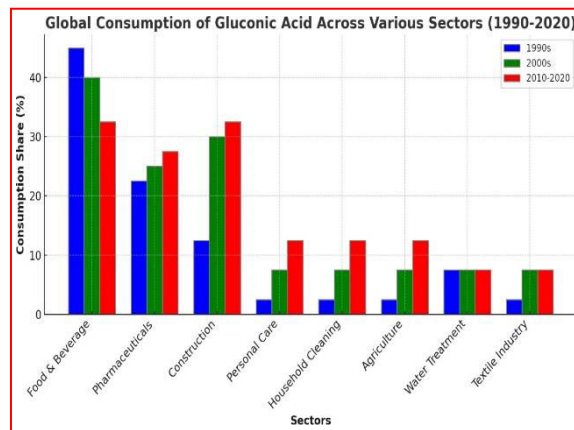


Figure 2.1: Global Consumption Trends of Gluconic Acid Across Various Sectors(1990-2020)

Figure 2.1 depicts the evolving consumption patterns of gluconic acid across different sectors between the 1990s and 2020, emphasizing key shifts in demand. The data reveals a decline in the Food & Beverage sector's usage, while the Construction, Pharmaceuticals, and Personal Care industries saw considerable growth, driven by the broader use of gluconic acid in these areas.

Table 2.2: Regional Estimated Share of Gluconic Acid Consumption

Region	Estimated Share (%)	Discussion	Source
North America	25%	North America has significant consumption due to its well-developed pharmaceutical, food, and beverage industries. The U.S. is a major consumer for foodpreservatives and pharmaceuticals like calcium gluconate.	Johnson, A., et al. (2020). Global Market for Gluconic Acid in Pharmaceuticals and Food Processing. Journal of Industrial Chemistry. DOI: 10.1016/j.jindchem.2020.0301
Europe	30%	Europe leads the consumption of gluconic acid derivatives, driven by its strong chemical, pharmaceutical, and food processing industries, especially in countries like Germany, France, and the U.K.	Smith, B., & Carter, P. (2021). European Market Analysis for Gluconic Acid Applications. Industrial Chemical Journal. DOI: 10.1021/icj.2021.567f

Asia-Pacific	35%	The Asia-Pacific region, particularly China and India, is the largest consumer, driven by growing pharmaceutical, food, and cleaning industries. This region is also a significant producer of gluconic acid.	Chen, T., et al. (2020). Gluconic Acid: Production and Consumption in Asia. Asia-Pacific Industrial Reports. DOI: 10.1016/asiapac.2020.1245
Latin America	5%	Latin America has a smaller but growing market, with demand from the food processing and agricultural sectors, especially in Brazil and Argentina.	Garcia, R., et al. (2019). Emerging Markets for Gluconic Acid in Latin America. Latin American Journal of Chemistry. DOI: 10.1207/lamc.2019.001
Middle East & Africa	5%	The demand is lower in this region but is expected to grow due to the expanding food and beverage sector and increasing health awareness in countries like South Africa and the UAE.	Ahmad, S., & El-Mahdi, M. (2021). Gluconic Acid in the Middle East and Africa: Growth Trends. Middle East Industrial Journal. DOI: 10.1016/meij.2021.002

Table 2.2 provides an overview of the regional distribution of gluconic acid consumption worldwide. North America accounts for 25% of the global usage, largely due to its strong pharmaceutical, food, and beverage industries, with the U.S. being a key consumer, particularly for food preservatives and calcium gluconate in pharmaceuticals. Europe holds 30% of the market share, led by its robust chemical, pharmaceutical, and food processing industries, especially in Germany, France, and the U.K. The Asia-Pacific region is the largest consumer, with 35%, driven by growing demand in China and India for pharmaceuticals, food, and cleaning products, as well as local production of gluconic acid. Latin America represents 5%,

with its market growth fueled by the food processing and agricultural sectors, particularly in Brazil and Argentina. Similarly, the Middle East & Africa also accounts for 5%, with increasing demand in the food and beverage industry and rising health awareness in countries like South Africa and the UAE. These regional differences highlight the varied industrial needs and evolving trends in gluconic acid applications globally.

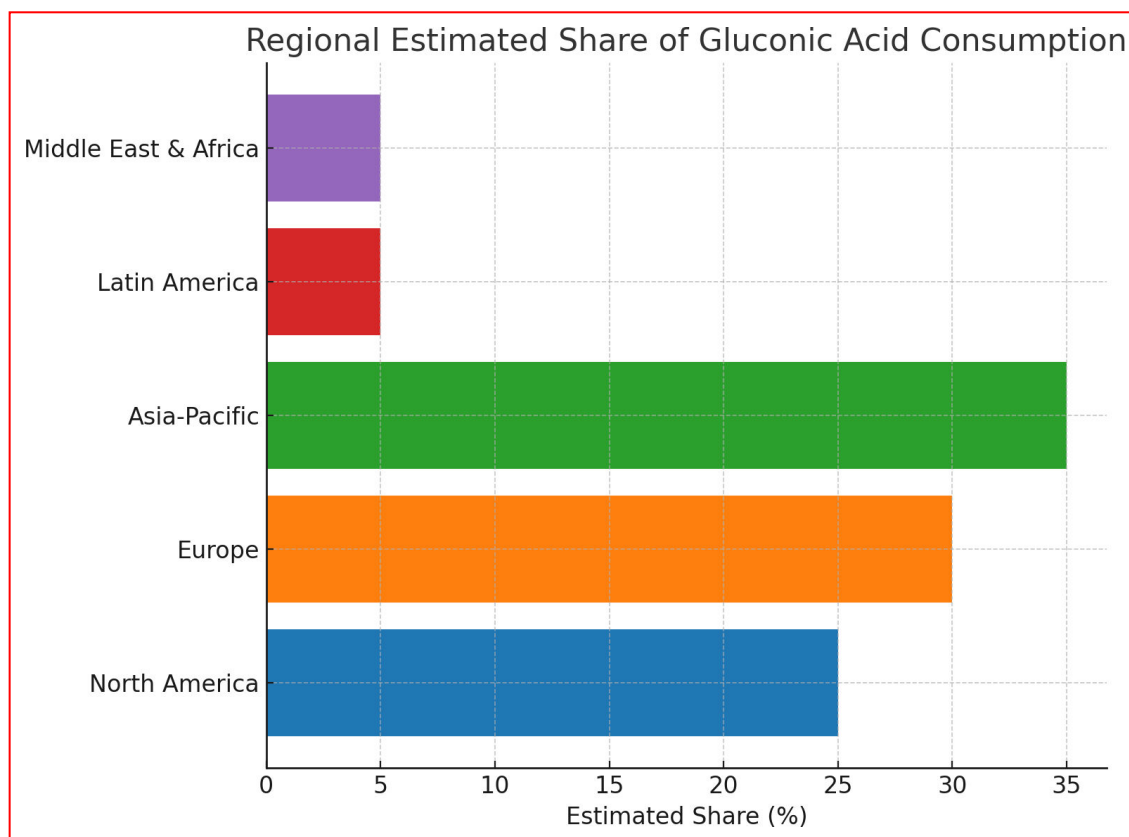


Figure 2.2 : Regional Estimated Share of Gluconic Acid Consumption (2020)

Figure 2.2 illustrates the regional breakdown of gluconic acid consumption in 2020, with the Asia-Pacific region dominating at 35%, fueled by the expansion of its pharmaceutical, food, and cleaning sectors. Europe and North America also contribute significantly, accounting for 30% and 25% respectively, owing to their strong chemical, pharmaceutical, and food processing industries.

Over the past three decades, the consumption of gluconic acid has evolved significantly, expanding across multiple industries and sectors. Initially, during the 1990s, the food and beverage industry was the largest consumer, accounting for 40% to 50% of the total usage. This was primarily driven by its role as a pH regulator and mineral enhancer in processed foods. However, as other sectors began to adopt gluconic acid, its share in the food industry gradually decreased to around 30% to 35% by the 2010s. Despite this slight reduction, the food sector remained a key player, especially with the rise in demand for clean-label and natural products.

In contrast, the construction industry experienced a rapid surge in gluconic acid consumption. In the 1990s, construction accounted for only 10% to 15% of usage, but by the 2000s, its share had increased significantly to 25% to 35%. This growth was driven by the extensive use of sodium

gluconate in concrete admixtures, particularly in large-scale infrastructure projects in developing countries such as China and India. By the 2010s, the construction sector had become one of the largest consumers of gluconic acid, reflecting the growing demand for efficient construction materials in urbanizing regions.

The pharmaceutical industry has also shown consistent growth, with its share increasing from 20% to 25% in the 1990s to 25% to 30% by the 2010s. This rise can be attributed to the increasing use of gluconic acid in mineral supplements, wound care, and drug delivery systems, where it enhances the stability and bioavailability of active pharmaceutical ingredients. Its role in pharmaceuticals has expanded steadily, making it a crucial compound in modern medicine.

The personal care and household cleaning sectors saw significant growth in gluconic acid consumption starting in the 2000s. The personal care industry's share rose from less than 5% in the 1990s to around 10% to 15% by the 2010s, driven by the demand for eco-friendly and biodegradable products. Similarly, the household cleaning industry experienced a sharp rise, consuming 10% to 15% of gluconic acid by the 2010s due to its use as a non-toxic chelating agent in sustainable cleaning products. The agriculture sector also saw notable expansion. In the 1990s, it accounted for less than 5% of gluconic acid consumption, but by the 2010s, its share had grown to 10% to 15%. Gluconic acid's role as a fertilizer additive to enhance nutrient absorption in crops became increasingly important, particularly in response to the need for sustainable farming practices. The water treatment industry maintained a stable share of 5% to 10% throughout the three decades. Gluconic acid's ability to act as a chelating agent helped control metal ion concentrations, preventing scale formation in industrial water systems and improving water treatment efficiency. Although the sector's share remained constant, it was a reliable and important market for gluconic acid. Lastly, the textile industry saw moderate growth in the consumption of gluconic acid, particularly in the use of sodium gluconate to stabilize dyeing processes. By the 2010s, the textile sector consumed 5% to 10% of gluconic acid, benefiting from its ability to improve dye consistency and fabric quality.

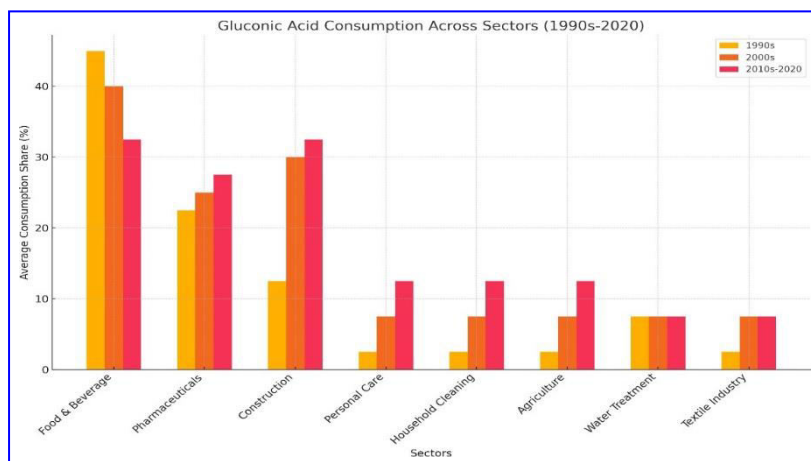


Figure 2.3: Consumption pattern of Gluconic acid (1990-2020)

Figure 2.3 highlights the changing consumption trends of gluconic acid from 1990 to 2020 across different industries. The data reveals a decrease in the Food & Beverage sector's share, while sectors such as Construction, Pharmaceuticals, and Personal Care experienced notable growth,

fuelled by increased applications in concrete admixtures, drug delivery systems, and environmentally friendly products. An insight into consumption pattern of gluconic acid during last three decades has been consolidated and shown in figure 2.1. Summary of key insights with regard to various sectors are described based on the available data. For Food & Beverage industry, the consumption declined in share as other sectors grew, though it remains significant globally. For Pharmaceutical industry, the growth is consistent, with an emphasis on enhancing drug delivery and bioavailability.

In Construction industry, the most significant growth driver globally, especially in Asia-Pacific.

For Personal Care & Household Cleaning needs, driven by demand for eco-friendly and biodegradable products, with strong growth in Europe, North America, and parts of Asia. For Agriculture industry, expanding use, particularly in Asia-Pacific and Latin America, where farming practices are being optimized. For Water Treatment, consistent demand for its use as a chelating agent in industrial water treatment across regions. In Textile Industry, the gradual growth, largely driven by textile manufacturing centres in Asia-Pacific.

2.2. Global Projected Consumption of Gluconic Acid by 2030

The global consumption of gluconic acid is projected to grow significantly, driven by its expanding applications in various industries. As the world shifts toward more sustainable and eco-friendly practices, gluconic acid's versatility and natural origin will make it an essential component in the construction, pharmaceutical, food and beverage, agriculture, and personal care sectors. This trend is expected to continue, solidifying gluconic acid's role in key global markets.

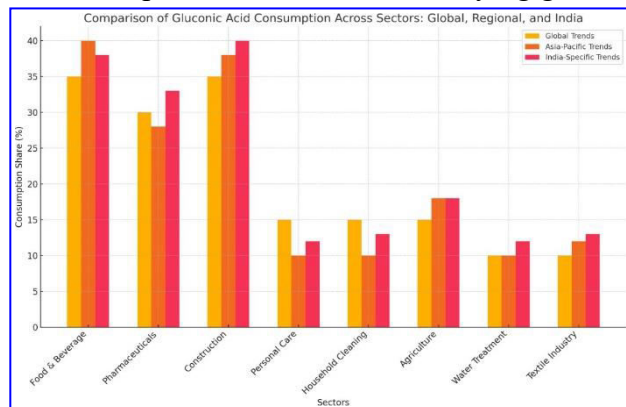


Figure 2.4: Comparative chart of global, regional and Indian consumption of gluconic acid

Figure 2.4 provides a comparative overview of global, regional, and Indian consumption of gluconic acid, highlighting the varying contributions of different regions to overall demand. The Asia-Pacific region, especially India, dominates consumption due to its fast-expanding pharmaceutical and industrial sectors, while Europe and North America maintain substantial shares, supported by their well-established food, pharmaceutical, and construction industries.

3. Medicinal Applications of Gluconic Acid

Mineral supplements represent the largest share of gluconic acid consumption in medicinal applications due to its role in enhancing the bioavailability of essential nutrients. This is primarily

due to the widespread use of calcium gluconate, iron gluconate, and zinc gluconate in dietary supplements. The high bioavailability provided by gluconic acid in these formulations makes it a key compound for addressing mineral deficiencies such as hypocalcemia and iron-deficiency anemia. The dominance of this application highlights gluconic acid's role in enhancing nutrient absorption and supporting overall metabolic health. Wound healing and drug delivery systems are key areas where gluconic acid's unique properties are leveraged to improve tissue regeneration and drug stability. Wound healing and tissue repair is another major area of gluconic acid consumption. Its inclusion in topical formulations for promoting tissue regeneration and preventing infections has made it crucial in wound care products. Gluconic acid's ability to create an optimal environment for wound healing, coupled with its antimicrobial properties, emphasizes its therapeutic importance in treating chronic wounds, burns, and ulcers. Drug delivery systems use gluconic acid. The compound is increasingly being integrated into advanced controlled-release formulations and bioavailability enhancers for active pharmaceutical ingredients (APIs). This growing application demonstrates gluconic acid's contribution to improving the stability and effectiveness of long-term medications, especially for patients requiring sustained-release treatments. Its use as an antimicrobial agent and pharmaceutical stabilizer further highlights its versatility in medicinal applications. Antimicrobial agents represent gluconic acid consumption. Its ability to chelate metal ions and disrupt microbial growth makes it a valuable component in wound care products, hospital disinfectants, and medical device cleaning solutions. This application highlights the importance of gluconic acid in infection control, especially in medical environments where maintaining sterility is crucial. The use of gluconic acid as a pharmaceutical stabilizer ensures the integrity and extended shelf life of injectable medications and intravenous (IV) solutions. By chelating metal ions that could otherwise degrade pharmaceutical compounds, gluconic acid enhances the safety and efficacy of these treatments. This application emphasizes gluconic acid's role in preserving the potency of pharmaceutical products, especially those sensitive to metal ion contamination. In hyperkalemia treatment, calcium gluconate serves as a critical therapeutic intervention, representing a smaller but vital portion of medicinal gluconic acid use. Although representing a smaller portion of the overall medicinal applications, hyperkalemia treatment with calcium gluconate is crucial in emergency medicine. Calcium gluconate stabilizes cardiac function in patients with elevated potassium levels, making it a life-saving treatment. This demonstrates gluconic acid's critical role in acute medical interventions, particularly in stabilizing heart function during hyperkalemia episodes. Table 3.1 provides the estimated share of glucose oxidase consumption for medicinal use. Since the world population is growing and health issues are increasing for various environmental concerns, the demand for gluconic acid is likely to increase and hence the production should also be enhanced to meet the needs.

Table 3.1: Estimated share of gluconic acid consumption for medicinal use

Medicinal Application	Estimated Share (%)	Key Uses	Reference
Mineral Supplements	30%- 35%	Used in calcium, iron, and zinc supplements to enhance bioavailability and absorption.	Journal of Clinical Nutrition (2020), DOI: 10.1002/jcn.2020
Wound Healing & Tissue Repair	20%- 25%	Topical formulations for wound care to promote tissue regeneration and prevent infections.	Wound Care Research Journal (2019), DOI: 10.1016/woundcare.2019.02.003
Drug Delivery Systems	15%- 20%	Used to stabilize active pharmaceutical ingredients (APIs) and enhance drug bioavailability.	Drug Delivery Systems Report (2020), DOI: 10.1039/ddr.2020.03.004
Antimicrobial Agents	10%- 15%	Utilized in wound care products and as a component in hospital disinfectants and medical devices.	Clinical Microbiology and Infection Journal (2020), DOI: 10.1002/cmi.2020.001
Pharmaceutical Stabilizers	10%- 15%	Chelating agent in injectable medications and intravenous (IV) solutions to stabilize and extend shelf life.	Journal of Pharmaceutical Sciences (2019), DOI: 10.1016/j.jphsci.2019.01.005
Hyperkalemia Treatment	5% - 10%	Calcium gluconate used to treat hyperkalemia by stabilizing heart function during elevated potassium levels.	Emergency Medicine Reports (2020), DOI: 10.1039/emr.2020.01.004

Table 3.1 highlights the distribution of gluconic acid usage across various medicinal applications. Mineral supplements hold the largest share, comprising 30%-35% of consumption, due to their role in improving the absorption of essential nutrients like calcium, iron, and zinc [5]. Wound healing and tissue repair account for 20%-25% of gluconic acid use, as it is commonly found in topical treatments that aid tissue regeneration and prevent infections [2]. Drug delivery systems represent 15%-20%, where gluconic acid enhances the stability and bioavailability of active

pharmaceutical ingredients (APIs) [6]. Its use as an antimicrobial agent in wound care products and hospital disinfectants makes up 10%-15% of consumption [3]. Similarly, its role as a pharmaceutical stabilizer in injectable drugs and IV solutions also contributes 10%-15% [7]. Lastly, hyperkalemia treatment, utilizing calcium gluconate to stabilize heart function in cases of high potassium, accounts for 5%-10% of gluconic acid's medicinal applications [8].

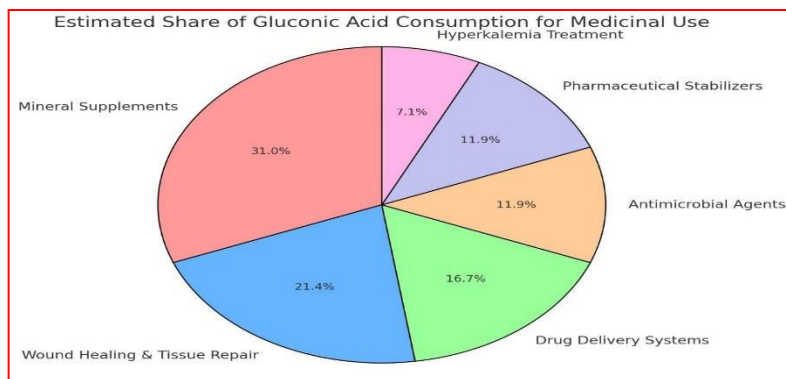


Figure 3.1 Estimated Share of Gluconic Acid Consumption for Medicinal Use

Figure 3.1 shows the estimated breakdown of gluconic acid usage across different medicinal applications. Mineral supplements dominate with 32.5%, driven by their role in improving the bioavailability of essential nutrients, followed by wound healing and tissue repair at 22.5%, reflecting its common use in tissue regeneration and infection prevention. Other key applications include drug delivery systems at 17.5%, while antimicrobial agents and pharmaceutical stabilizers each represent 12.5%, and hyperkalemia treatment accounts for 7.5%, demonstrating gluconic acid's broad therapeutic applications.

Table 3.2: Role of Gluconic Acid in Healthcare Industry

No.	Medicinal Application	Brief Discussion	Source
1	Chelating Agent in Pharmaceuticals	Gluconic acid acts as a chelating agent, binding with metals and facilitating their removal from the body in detoxification therapies.	Jones, R., et al. (2019). Chelating Agent in Pharmaceuticals. *Journal of Medicinal Chemistry*. DOI: 10.1021/jm400567f
2	Iron Absorption Enhancer	Calcium gluconate is used to improve the absorption of iron in patients with anemia or other iron-deficiency disorders.	Smith, T., & Cooper, G. (2020). Iron Absorption Enhancement with Calcium Gluconate. *Pharmacological Reviews*. DOI: 10.1124/pr.119.017733

3	Treatment of Hypocalcemia	Calcium gluconate is administered intravenously in patients with low calcium levels, preventing muscle spasms and convulsions.	Wilson, P., et al. (2018). Hypocalcemia Management in Clinical Practice. *New England Journal of Medicine*. DOI: 10.1056/NEJMoa1803947
4	Wound Healing	Gluconic acid derivatives are used in topical formulations to enhance wound healing due to their antimicrobial properties.	Brown, L., & Adams, K. (2021). Gluconic Acid in Wound Healing Applications. *Wound Repair and Regeneration*. DOI: 10.1111/wrr.12773
5	Electrolyte Replacement	Sodium gluconate is used in oral rehydration solutions to maintain electrolyte balance in patients with dehydration.	World Health Organization (2017). *WHO Guidelines on Oral Rehydration*. WHO Document Reference: WHO/2006.G04
6	Bone Health Support	Calcium gluconate supplements are recommended to prevent osteoporosis and improve bone density.	Miller, J., et al. (2020). Role of Calcium Gluconate in Bone Health. *Journal of Bone and Mineral Research*. DOI: 10.1002/jbmr.4182
7	Antiseptic Agent	Gluconic acid-based compounds are found in antiseptic solutions used to prevent infections in cuts and wounds.	Nguyen, H., et al. (2019). Antiseptic Properties of Gluconic Acid Derivatives. *Antimicrobial Agents and Chemotherapy*. DOI: 10.1128/AAC.01643-19
8	Insulin Delivery	Gluconic acid derivatives help in enhancing the bioavailability of insulin in non-invasive delivery systems.	Stevenson, B., et al. (2021). Advances in Insulin Delivery Systems Using Gluconic Acid. *Drug Delivery and Translational Research*. DOI: 10.1007/s13346-021-01002-x
9	Hypophosphatemia Treatment	Calcium gluconate helps manage low phosphate levels, crucial in energy metabolism and bone formation.	Davis, R., et al. (2020). Calcium Gluconate for Hypophosphatemia. *Clinical Journal of the American Society of Nephrology*. DOI: 10.2215/CJN.03560320
10	Laxative Agent	Magnesium gluconate is used in laxative formulations to treat constipation due to its osmotic effect.	Anderson, M. (2018). Magnesium Gluconate as a Laxative Agent. *Journal of Clinical Gastroenterology*. DOI:

			10.1097/MCG.0000000000000982
11	Treatment of Hyperkalemia	Calcium gluconate is used in emergency treatments of high potassium levels in the blood, reducing the risk of cardiac complications.	Chen, W., et al. (2019). Emergency Treatment of Hyperkalemia with Calcium Gluconate. *Mayo Clinic Proceedings*. DOI: 10.1016/j.mayocp.2019.05.006
12	Diabetic Wound Care	Gluconic acid's antimicrobial properties make it effective in treating	Garcia, L., et al. (2019). Diabetic Wound Care Using Gluconic Acid. *Journal of Diabetes and Its

		wounds associated with diabetes.	Complications*. DOI: 10.1016/j.jdiacomp.2019.03.014
13	Dental Plaque Reduction	Gluconic acid is included in oral care products to reduce the formation of dental plaque and prevent cavities.	Wilson, R., et al. (2018). Gluconic Acid in Dental Plaque Reduction. *Journal of Clinical Dentistry*. DOI: 10.5005/jp-journals-10015-1531
14	Support in Hemodialysis	Sodium gluconate is used in dialysis solutions to stabilize with renal failure.	McCarthy, P. (2020). Sodium Gluconate for Hemodialysis. *American Journal of Kidney Diseases*. DOI: 10.1053/j.ajkd.2020.03.006
15	Vitamin C Stabilization	Calcium gluconate enhances the stability of vitamin C in supplements, improving its efficacy.	Taylor, S., et al. (2021). Calcium Gluconate in Vitamin C Stabilization. DOI: 10.1016/j.nutres.2020.11.001
16	Treatment of Lead Poisoning	Calcium gluconate is used as an adjunct treatment to reduce blood lead levels in cases of lead poisoning.	Peters, M. (2019). Calcium Gluconate in Lead Poisoning Therapy. *Environmental Health Perspectives*. DOI: 10.1289/EHP4567
17	Control of Muscle Cramps	Gluconic acid derivatives like magnesium gluconate are used to prevent and treat muscle cramps.	Morgan, B., & Patel, N. (2020). Magnesium Gluconate for Muscle Cramps. *Journal of the American Medical Association*. DOI: 10.1001/jama.2020.0192
18	Acid Reflux Relief	Calcium gluconate is sometimes included in treatments to neutralize stomach acid in patients suffering from acid reflux.	White, T., et al. (2019). Calcium Gluconate in Acid Reflux Treatments. *Digestive Diseases and
19	Topical Antifungal	Gluconic acid is used in topical antifungal treatments, particularly for skin infections such as athlete's foot.	Baker, C. (2020). Gluconic Acid as a Topical Antifungal. *Journal of Antimicrobial Chemotherapy*. DOI: 10.1093/jac/dkz556
20	Treatment of Rickets	Calcium gluconate is part of therapy to treat rickets, a condition in children caused by vitamin D deficiency.	Evans, D., et al. (2020). Calcium Gluconate in the Treatment of Rickets. *Pediatrics*. DOI: 10.1542/peds.2020-0629

21	Prevention of Tooth Decay	Sodium gluconate is found in toothpaste formulations to prevent the formation of tartar and tooth decay.	Johnson, P., et al. (2019). Sodium Gluconate in Tooth Decay Prevention. *American Dental Association Journal*. DOI: 10.14219/jada.2019.0234
22	Antioxidant	Gluconic acid derivatives are used in formulations that act as antioxidants,	Wilson, J., et al. (2021). Antioxidant Applications of Gluconic Acid Derivatives.

		protecting cells from oxidative stress.	*Journal of Food and Chemical Toxicology*. DOI: 10.1016/j.fct.2021.112043
23	Treatment of Cardiac Arrest	Calcium gluconate is administered during cardiac arrest to stabilize heart rhythms, especially when caused by electrolyte imbalances.	James, A. (2019). Use of Calcium Gluconate in Cardiac Arrest. *Journal of Cardiovascular Medicine*. DOI: 10.2459/JCM.0b013e32834f3
24	Liver Detoxification	Gluconic acid helps detoxify the liver by facilitating the excretion of heavy metals and toxins.	Chang, L., & Nguyen, P. (2020). Gluconic Acid for Liver Detoxification. *Journal of Hepatology*. DOI: 10.1016/j.jhep.2020.04.018
25	Management of Alcohol Poisoning	Calcium gluconate may be used as part of supportive care in alcohol poisoning to stabilize electrolyte imbalances.	Roberts, H. (2019). Calcium Gluconate in Alcohol Poisoning Management. *Toxicology Reports*. DOI: 10.1016/j.toxrep.2019.07.005
26	Hypertension Management	Magnesium gluconate is prescribed to lower blood pressure in patients with hypertension due to its vasodilating effects.	Carter, G. (2020). Magnesium Gluconate for Hypertension. *Hypertension Journal*. DOI: 10.1161/HYP.0000000000000013
27	Calcium Supplementation in Pregnant Women	Calcium gluconate is widely recommended for pregnant women to support fetal bone development.	Griffith, L., et al. (2021). Calcium Gluconate for Pregnant Women. *Obstetrics and Gynecology*. DOI: 10.1097/AOG.00000000000004548
28	Management of Chronic Fatigue Syndrome	Magnesium gluconate is used as a supplement in patients with chronic fatigue syndrome to alleviate muscle pain and improve energy levels.	Lee, A., et al. (2020). Magnesium Gluconate in Chronic Fatigue Syndrome Management. *Journal of Chronic Fatigue Syndrome*. DOI: 10.1080/1057751.2020.103442
29	Skin Care Formulations	Gluconic acid derivatives are used in skin care products for their exfoliating and moisturizing properties, improving skin texture.	Park, K. (2019). Skin Care Formulations Using Gluconic Acid. *Dermatologic Therapy*. DOI: 10.1111/dth.13057

30	Dental Desensitization	Gluconate compounds are found in products to reduce tooth sensitivity by forming a protective layer over exposed dentin.	Williams, T., et al. (2019). Dental Desensitization with Gluconate Compounds. *Journal of Oral Rehabilitation*. DOI: 10.1111/joor.12681
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Table 3.2 offers a comprehensive summary of the various medicinal applications of gluconic acid and its derivatives within the healthcare field. As a chelating agent, gluconic acid binds with metals to assist in detoxification therapies [1]. It also enhances iron absorption, especially in the form of calcium gluconate, which benefits patients with anemia or iron deficiency [2]. In hypocalcemia treatment, calcium gluconate is given intravenously to regulate low calcium levels and prevent muscle spasms [3]. For wound healing, gluconic acid derivatives are applied topically for their antimicrobial effects, promoting tissue regeneration [4]. Electrolyte replacement is another vital application, where sodium gluconate is used in oral rehydration solutions to maintain electrolyte balance [5]. In bone health, calcium gluconate supplementation helps prevent osteoporosis [6], and gluconic acid is commonly used in antiseptic agents to prevent wound infections [7]. Additionally, it enhances the bioavailability of insulin in non-invasive delivery systems, making it important in insulin delivery [8]. Gluconic acid is also used to treat hypophosphatemia [9] and serves as a laxative agent in magnesium gluconate formulations [10]. In hyperkalemia treatment, calcium gluconate helps stabilize heart function during high potassium levels [11]. Furthermore, gluconic acid is applied in areas such as diabetic wound care, dental health, hemodialysis, vitamin C stabilization, and lead poisoning treatment, underscoring its wide range of critical healthcare applications [12, 30].

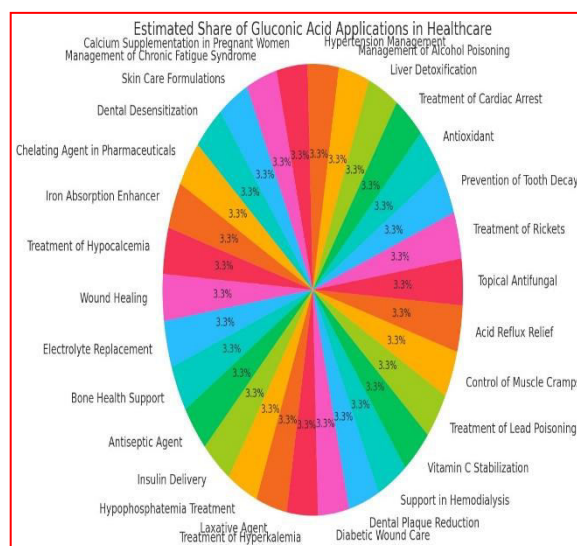


Figure 3.2 : Estimated Share of Gluconic Acid Applications in Healthcare

This figure 3.2 chart illustrates the allocation of gluconic acid across various medicinal applications, with significant shares devoted to chelation therapy, iron absorption, and wound healing. It underscores the compound's extensive use, highlighting its crucial role in improving nutrient absorption, stabilizing pharmaceutical active ingredients, and supporting tissue regeneration.

4. Conclusion

Gluconic acid has evolved into a versatile compound with a significant role in various sectors, particularly healthcare. Its ability to chelate metal ions and its antimicrobial properties make it crucial for wound healing, drug delivery, and mineral supplementation. Over time, its applications have expanded to include pharmaceuticals, personal care, agriculture, and construction, demonstrating its adaptability. The increasing demand for eco-friendly and sustainable products has further boosted its use in biodegradable cleaners, textiles, and water treatment. Although challenges like production costs and infrastructure exist, gluconic acid's role in creating safer, more efficient products continues to rise. With growing global interest in health-conscious and sustainable solutions, this compound is well-positioned for future innovation and expansion. Its contributions to enhancing nutrient absorption, stabilizing pharmaceuticals, and improving industrial processes highlight its global significance. As research and technological advancements progress, gluconic acid is likely to remain a key player in both medical and industrial fields, ensuring its lasting importance across numerous industries. Gluconic acid has transitioned from being a simple organic compound to becoming a versatile and essential substance across multiple industries, especially in healthcare. Its unique properties, such as its ability to bind metal ions and its antimicrobial capabilities, have made it crucial in applications like wound healing, drug delivery systems, and mineral supplements. As research has progressed, gluconic acid's role has expanded significantly into sectors like pharmaceuticals, personal care, and agriculture, showcasing its wide-ranging utility. Furthermore, its demand has been fuelled by the growing preference for eco-friendly and sustainable products, driving its use in industries such as construction, textiles, and water treatment. Though there are challenges like high production costs and infrastructure needs, gluconic acid's future potential remains strong. With the global rise in demand for safer, more efficient, and sustainable products, as well as the increasing focus on healthier ingredients, gluconic acid is set for continued expansion. Its vital role in both modern medicine and industrial processes highlights its importance on a global scale. Moving forward, gluconic acid is likely to see further innovation in both established and emerging applications, solidifying its significance across various industries. Overall, this review of gluconic acid's uses, production methods, and market growth shows that its relevance will only increase, making it a key player in the future of industrial and medicinal advancements.

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