Architecture Image Studies

Vol.7, Issue 1, pp.2261-2288, 2026
DOI: https://doi.org/10.62754/ais.v7i1.1208

https://journals.ap2.pt/index.php/ais/index

Advancing Carbon Dioxide Utilization Technologies for Sustainable Food Production in the GCC

Mohammed Saleh Al Ansari[1], ZEBA KHAN[2], Hajabanu Shaikh Mohammed Essa[3], Mohd Arif[4]

Abstract

The food industry is a significant contributor to emissions of carbon dioxide worldwide because of its energy intensive nature of packaging, processing, refrigeration and extended supply chains. Intense climate, fossil fuel prevents energy, desalinated water, and food imports boost these emissions in dry location like Gulf Cooperation Council (GCC). Carbon dioxide is functional medium for fermentation, refrigeration, carbonation, microbial control, and preservation in food industry, which could be an appropriate platform to absorb carbon and exertion. CO2-reuse paths in the food business: A detailed analysis, with an emphasis on GCC economies. Physical, chemical, and biological pathways of usage are being evaluated based on technological food hygiene, maturity, and fusing potential. The priority is on functional applications such as modified environment packaging, cryogenic freezing, dairy processing, beverage carbonation, and developing carbon to food pathways like microphytes protein production, microbial lipid synthesis, and synthesis carbohydrates. Patent landscape analysis weighs revolution trends and commercial attentiveness, and procedure, coast effective, and social obstacles to large scale adoption are evaluated. CO2 recycle in the food industry is an auspicious decarbonization approach for dry areas with long term promise for food security if governmental frameworks, industrial incorporation, and communal assurance are formed.

Keywords: *Carbon Absorption, Carbon Dioxide, Food Industry, Microphytes Protein, Cryogenic Freezing, Decarbonization.*

Introduction

The most pressing issues facing modern industrial society is overall variety of the environment, which is mostly influenced by human greenhouse gas emissions. Carbon dioxide is the main contributor to emissions, outstanding to its significant volume and determined atmospheric persistence (IPCC, 2023). Food systems, which include food processing, agricultural production, refrigeration, packaging, transportation, and waste management are thought to be responsible for nearly one-third of all anthropogenic greenhouse gas emissions, even though energy invention and transportation are commonly cited as the main sources of emissions. (Crippa et al., 2021).

The impact of the food industry on climate change is significantly considerable due to its dependence on energy intensive methods including pasteurization, heat processing, sterilization, continuous cold chain refrigeration and drying. (Ladha-Sabur et al., 2019; Shabir et al., 2023). These operations are aggravated by rigorous packaging requirements and extensive distance logistics, especially in areas with limited homegrown food production capabilities. With the global demand for food intensifying due to urbanization, population expansion, and evolving ingesting patterns, manufactures linked to food production are likely to rise unless significant moderation initiatives are proclaimed.

[1] Associate Professor, College of Engineering, Department of Chemical Engineering University of Bahrain Bahrain, Email: malansari.uob@gmail.com, https://orcid.org/0000-0001-9425-0294
[2] Applied College, Jazan University Jazan – 45142 Kingdom of Saudi Arabia, Email: zabumazeedullah@jazanu.edu.sa.
[3] Jazan University Jazan – 45142 Kingdom of Saudi Arabia, Email: hshaikh@jazanu.edu.sa

[4] Department of IT, Computer Lab Section Jazan University Jazan Saudi Arabia, Email: makhtar@jazanu.edu.sa

In the GCC countries, the carbon power of food systems is improved by environmental restraints and structural. Tremendous ambient temperatures need persistent refrigeration and meticulous storage settings, while restricted arable land and freshwater insufficiency promote heavy reliance on food imports and detoxification dependent processing (FAO, 2025). Electricity production in the region remains largely fossil fuel based, strongly binding agricultural production to CO_2 productions from the power region. Therefore, predictable emission reduction methods based unconditionally on energy effectiveness or renewable energy changeover are normally inadequate to achieve deep decarbonization of the food manufacturing in the GCC.

Carbon capture and utilization (CCU) have risen as a feasible adjunct to conservative mitigation approaches by simplifying the conversion of CO_2 from a production liability into a valuable resourcefulness (Hepburn et al., 2019; Kim et al., 2022). In divergence to carbon capture and storage (CCS), which aims to permanently segregate CO_2 from the mesosphere, carbon capture and utilization (CCU) endeavors to reintegrate composed CO_2 into industrial value restraints. The food industry is specifically located in this environment as CO_2 is significantly consumed as a food grade processing agent, specifically in fermentation regulation, carbonation, modified atmosphere packing, microbial inactivation, and refrigeration (Kaliyan et al., 2007; Jayas & Jeyamkondan, 2002).

The integral compatibility sets the food region separately from other CCU application areas, such as manufacture or fuels, where the establishment of markets and regulatory approval pose significant barriers. The reuse of CO_2 in food organizations can provide food organizations with tremendous benefits, including better quality products with longer shelf life, less product waste, and lifecycle reduction in production. In addition, new synthetic and biological methods now enable direct retention of the CO_2 into lipids, proteins, and carbohydrates for the subsequent conservation and hence the possibility of carbon-based food production (CBS) systems in a system totally free of terrestrial and freshwater resources. (Cai et al., 2021; Janssen et al., 2022).

Despite this potential, the use of CO_2 reuse in the food industry is limited by important technological, social, legal, and economic barriers. Adoption is still limited by an uncoordinated regulatory structure, high purification and capture energy requirements, unclear market acceptance of food products generated by CO_2, and stringent food grade safety legislation. (Cuéllar-Franca & Azapagic, 2015; Dziejarski et al., 2023). Since its regulations surrounding CCU in food systems are still fledgling, the GCC is faced with this predicament.

Carbon Dioxide Emission: An Overview of the Food Sector’s Emission Issues

Carbon dioxide releases from the food industry provide a universal and organizational concern that extends well afar simple farming observes. Climate extremes, reliance on imports, energy consumption associated with detoxification, and fossil fuel-dominated energy systems all contribute to the carbon intensity of food production in the Gulf Cooperation Council (GCC), which includes the United Arab Emirates, Qatar, Saudi Arabia, Kuwait, Bahrain, and Oman. In contrast to temperate locations, the GCC has consistently high ambient temperatures for food processing and preservation, frequently surpassing 40 °C for persistent periods of time. Indirect CO_2 emissions are greatly increased by the substantial reliance on energy-intensive refrigeration, cold-chain logistics, controlled-atmosphere storage, and thermal food processing imposed by this climate reality. Just the use of electricity for refrigeration accounts for a large portion of the region's food-sector emissions, especially in supply chains for dairy, beef, and frozen foods. From a process perspective, there are three main ways that the GCC food business releases CO2:

1. Direct combustion emissions from boilers, dryers, pasteurizers, sterilizers, and ovens that use fossil fuels in the production of food.
2. Emissions from indirect electricity that are connected to refrigeration, air conditioning, cooling, and packaging processes that are run by grids that rely on gas and oil.
3. Embedded supply chain emissions, encompassing imported raw materials, package manufacturing, transportation, and waste management.

The region's limited arable land and freshwater shortages, which force food imports, the usage of desalinated water, and controlled-environment agriculture, further exacerbate these emissions. Food production is inextricably linked to power generating emissions due to the additional energy–carbon coupling introduced by desalination, a vital water source for food processing in the GCC.

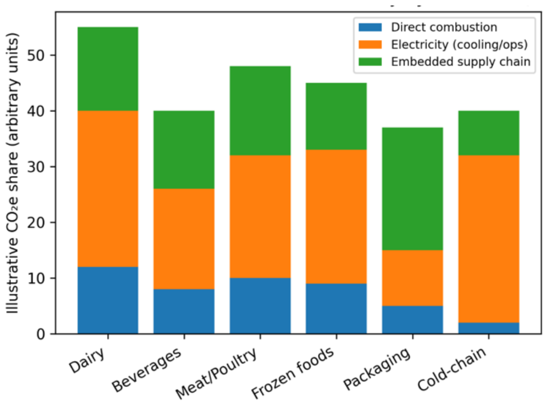


Figure 1. CO_2 emission sources in the GCC food industry by subsector

Figure 1 shows CO_2 emissions distribution in important food industry subsectors in the Gulf Cooperation Council (GCC), such as dairy processing, beverage manufacturing, meat and poultry production, frozen food processing, packaging, and cold-chain logistics. The graphic shows that energy-intensive operations—particularly refrigeration, thermal processing, and cold-storage logistics—drive food-sector emissions. High ambient temperatures in the GCC food system boost electricity demand for cooling and preservation, leading to indirect CO_2 emissions from fossil-fuel power generation, unlike in temperate countries. Import-dependent food supply chains contribute significantly to the carbon footprint due to emissions from transportation, packaging, and long-distance logistics. Disaggregating emissions by subsector gives this figure a quantifiable basis for assessing GCC mitigation and CCU measures. The highest emission subsectors, like dairy, beverages, and frozen foods, have the greatest potential for CO_2 reuse due to their use of food-grade carbon dioxide for carbonation, modified atmosphere packaging, refrigeration, and microbial control. The figure shows why CCU deployment should be prioritized in food subsectors with co-located emission intensity and utilization potential to maximize decarbonization impact and minimize infrastructure redundancy (Crippa et al., 2021; Ladha-Sabur et al., 2019; FAO, 2025).

Table 1. CO_2 Emission Sources in the GCC Food Industry

Food subsector	Key unit operations	Primary CO_2 source	Relative emission intensity	GCC-specific drivers
Dairy processing	Pasteurization, chilling, cold storage	Electricity + thermal fuel	High	Continuous refrigeration, high hygiene standards
Beverage production	Carbonation, bottling, refrigeration	Electricity + fermentation CO_2	Medium–High	Large volumes, high cooling demand
Meat & poultry	Slaughtering, chilling, MAP, freezing	Electricity + thermal fuel	High	Cold-chain dependence, food safety
Frozen foods	IQF freezing, cold storage	Electricity	Very high	Ambient temperatures >40 °C
Food packaging	Polymer processing, forming	Electricity + materials	Medium	High packaging demand for imports
Cold-chain logistics	Refrigerated transport, storage	Diesel + electricity	Very high	Long transport distances, heat stress

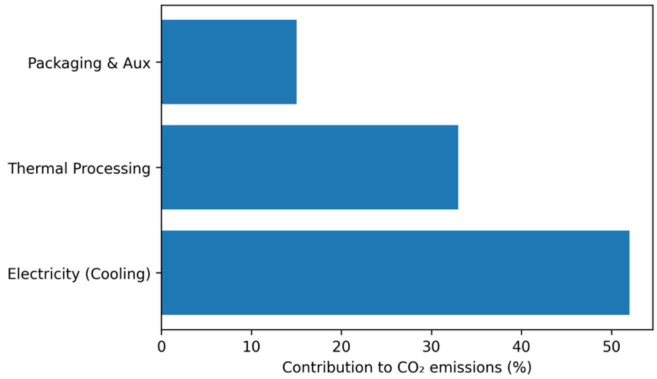


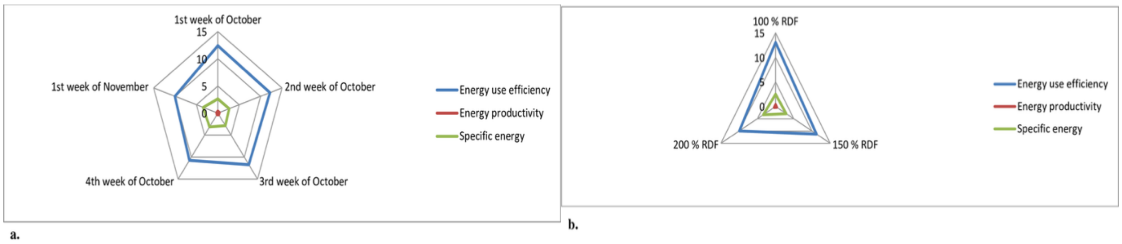
Figure 2. Energy–carbon coupling in GCC food systems

Figure 2 shows the relationship between energy use and CO_2 emissions in GCC food systems using a Sankey-style representation. The picture shows how main energy inputs, such as fossil-fuel-derived electricity and thermal energy, impact food-industry processes including refrigeration, thermal processing, packaging, and cold-chain logistics, ultimately resulting in CO_2 emissions. In the GCC, high ambient temperatures require continuous refrigeration, therefore cooling and preservation activities use a disproportionate amount of energy. Unlike in temperate countries, cooling demand dominates operational energy usage and emissions, making food security and carbon-intensive energy systems interdependent. By providing process water for food manufacture, desalination-linked electricity demand indirectly increases food-sector emissions. The chart shows why incremental efficiency increases alone cannot separate food production from emissions in the GCC. Rather, it highlights the importance of systemic mitigation strategies, such as carbon capture and utilization (CCU). The schematic enables the integration of the CO_2 reuse pathway into energy-intensive food operations, converting emissions into process inputs and reinforcing the energy water food carbon nexus. (IPCC, 2023; Shabir et al., 2023) The food industry is one industry where CO_2 serves as a process benefit instead of a byproduct.

The food sector of the GCC is best positioned for closed loop carbon management if capturing, purifying, and reusing systems comply with food grade standards. In the GCC, the reuse of CO_2 is fragmented and rarely exploited due to the absence of focused regulatory food grade CO_2 legislation, and region-specific techno-economic evaluations. To redress this divide, we need to move from emissions accounting to carbon systems engineering which can treat CO_2 as a resource in food production ecosystems rather than an external liability.

Mitigation Initiatives: Transitioning from Carbon Capture Towards Emission Eradication in GCC Food Industry

Conventional CO_2 reduction efforts in the food sector have focused on marginal efficiency enhancements and on production scrutiny after the emissions themselves, rather than total change. In the GCC, due to energy-intensive food systems, the fossil-fuel-driven power mix, and climatic dependence on refrigeration and controlled processing environments, these initiatives have done little. Therefore, there is growing realization that significant food industry decarbonization demands a shift from carbon management to carbon removal and reuse.



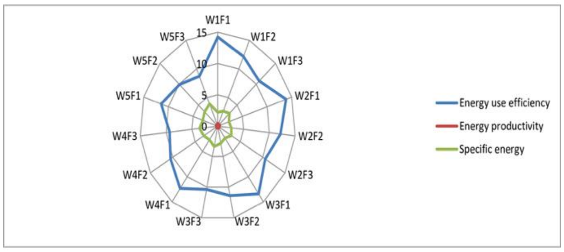


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Figure 3. Comparison of mitigation pathways for the GCC food industry

Figure 3 compares GCC food industry mitigation strategies like energy efficiency, renewable energy, CCS, and CCU. Food systems are compared by emission reduction potential, capital and operating expenses, scalability, regulatory compatibility, and food-grade appropriateness. Energy efficiency and renewable integration lower emissions, but cooling demand and fossil-dominated networks hinder them. CCS has high mitigation potential but low food-sector economic compatibility, regulatory complexity, and little operational benefits. CCU has low emission reduction potential but offers immediate benefits by reintegrating CO_2 into food processing, preservation, and packing. The graphic illustrates the benefits of CCU for GCC food systems, where CO_2 is already used for processing and geological storage is costly. The amount prevents simplification and supports the analysis's argument that CCU should supplement productivity and renewable methods in integrated decarbonization.

Emission Reduction to Carbon Systems Engineering

Food handling alleviation methods including improved logistics, high-efficiency motors, increased segregation, and limited electrification reduce energy usage but not carbon fluctuations. Though these efforts are essential, they do not address the structural issue of CO_2 emissions from fermentation, thermal processing, electricity generation, and fuel combustion. Carbon systems engineering integrates carbon capture, reuse, and valorization into food production workflows to rethink mitigation. Localized carbon loops are ideal for the GCC due to centralized food-processing zones, industrial clustering, and closeness to power and desalination plants.

Table 2. CO_2 strategies and its key limitations in the GCC food industry

Strategy	**CO_2 reduction potential**	**Energy penalty**	**Food-sector compatibility**	**Scalability in GCC**	**Key limitations**
Energy efficiency	Low–Moderate	None	High	High	Limited by cooling demand
Renewable electricity	Moderate	None	High	Medium	Grid intermittency
Carbon capture & storage (CCS)	High	High	Low	Low	Cost, infrastructure
Carbon capture & utilization (CCU)	Moderate	Low–Moderate	Very high	High	Purity, regulation
Carbon-to-food pathways	Very high (long-term)	High	Emerging	Low (current)	TRL, cost

Carbon Capture Routes Relevant to the Food Industry

The three basic categories of carbon capture technology that are relevant to the food sector are post-combustion, process-integrated, and biogenic capture routes.

Post-Combustion Capture in Food Processing Facilities

Existing food manufacturing plants' most mature and versatile method is post-combustion capture. CO_2-rich exhaust streams in GCC food facilities come from boilers, steam generators, ovens, dryers, CHP units, and thermal sterilization/pasteurization systems. High capture efficiency is achieved through chemical absorption employing amine-based solvents, even at low CO_2 partial pressures. Energy costs, solvent degradation, and food-grade contamination hazards limit its use in food-sector contexts. More food-industry-friendly alternatives such solid sorbents, membrane separation, and hybrid adsorption–

membrane systems have lower regeneration energy and better operating stability. Since waste heat is abundant in the GCC, heat-integrated capture technologies can reduce solvent regeneration energy. An underexplored yet promising mitigation approach is coupling capture units with refrigeration compressor or thermal processing line waste heat.

Process-Integrated and In-Situ Capture

The food business generates process-intrinsic CO_2 through fermentation, carbonation, and anaerobic digestion of organic waste, unlike heavy industries. High-purity, low-contaminant streams simplify and lower capture costs. Increased beverage and dairy production in GCC food facilities can achieve near-zero waste carbon cycles with in-situ CO_2 recovery. CO_2 can be compressed, filtered, and reused internally for carbonation, packaging changes, or microbial control, minimizing the need for industrial CO_2.

Table 3. CO_2 capture pathways applicable to food processing plants

Capture pathway	Typical CO_2 source in food plants	CO_2 purity (as-captured)	Energy requirement	Food-grade suitability	Key advantages	Key limitations	GCC relevance
Post-combustion chemical absorption (amines)	Boilers, ovens, dryers, CHP exhaust	Low–moderate (5–15 vol.% CO_2)	High (solvent regeneration)	Conditional (after polishing)	Mature technology; high capture efficiency	Energy penalty; solvent degradation; multi-stage purification needed	Feasible where waste heat is available; better suited for large plants
Adsorption (solid sorbents)	Combustion exhaust, mixed gas streams	Low–moderate	Moderate	Conditional	Lower regeneration energy; modular	Sorbent fouling; sensitivity to humidity	Attractive for decentralized GCC food plants
Membrane separation	Combustion exhaust, mixed streams	Low–moderate	Moderate	Conditional	Compact footprint; no solvents	Selectivity trade-offs; compression demand	Suitable where space is constrained
Fermentation off-gas recovery	Breweries, bakeries, dairy fermentation	High (>95 vol.% CO_2)	Low	High	Inherently food-grade; low purification cost	Limited to fermentative operations	Highly attractive for GCC beverage and dairy plants
Carbonation recovery systems	Beverage filling and bottling lines	Very high	Very low	Very high	Near-zero contamination; closed loops	Application-specific	Ideal for GCC soft-drink and bottled water industry
Biogenic capture (anaerobic digestion)	Food waste, wastewater treatment	High	Low–moderate	Conditional	Waste valorization; renewable CO_2	Variable gas composition; scale issues	Relevant where food waste management is integrated

Capture pathway	**Typical CO_2 source in food plants**	**CO_2 purity (as-captured)**	**Energy requirement**	**Food-grade suitability**	**Key advantages**	**Key limitations**	**GCC relevance**
Hybrid capture–biological systems	Flue gas + microalgae reactors	Variable	Moderate	Indirect	CO_2 fixation + biomass production	Lower TRL; operational complexity	Promising long-term option for GCC industrial clusters

Biogenic and Hybrid Capture Approaches

Utilizing biological processes such as microbial fixation and microalgae cultivation, biogenic CO_2 capture absorbs emissions and produces biomass. By producing and mitigating, these systems support food processing facilities and adhere to the principles of the circular economy. In areas like the Gulf Cooperation Council (GCC), where open cultivated land is scarce but industrial infrastructure is well-developed, hybrid techniques that combine physical capture with biological conversion are becoming more popular. To produce proteins, lipids, and carbohydrates, closed photobioreactors powered by collected CO2 provide regulated, scalable platforms.

Comparing Carbon Capture and Utilization with Carbon Capture and Storage

Carbon capture and storage (CCS) have been advocated as a decarbonization solution, however its food sector applications, especially in the GCC, are restricted. Infrastructure, legal frameworks, and long-term liability management for geological storage often conflict with food-sector economics. However, carbon capture and use (CCU) have many benefits like reducing emissions through reuse, generating revenue from value-added goods, reducing reliance on imported food-grade CO_2, and aligning with food safety and environmental goals.

CCU is a real-world and ascendable mitigation method for the GCC food commerce, specially when usage pathways are chosen based on purity, contiguity, and market demand.

Toward Emission Elimination

Accurate production eradication requires process restructuring and carbon-neutral manufacturing systems, not just apprehend and reuse. In the food industry, this involves:

- Executing low-carbon electricity for thermal procedures,
- Combining renewable energy with capture and utilization systems,
- Substituting fossil derived inputs with CO2 derived alternatives,
- Improving electronic carbon fluxes under manufacturing constraints.

The food industry is one example of integrated decarbonization in the GCC as national net-zero goals drive industrial policy. CCU, renewable energy, controlled environments and desalination in food production provide a supporting environment for closed loop carbon food systems.

Transforming Waste into Value: A Strategic Framework for CO_2 Utilization

The shift from carbon management to carbon valorization changes perceptions of industrial emissions. Given the food industry's reliance on CO_2 as a processing medium, this move is technically and economically feasible, especially in the GCC. The food business is ideal for closed-loop carbon reuse, as it currently includes CO_2 in numerous unit activities, unlike sectors that require new markets.

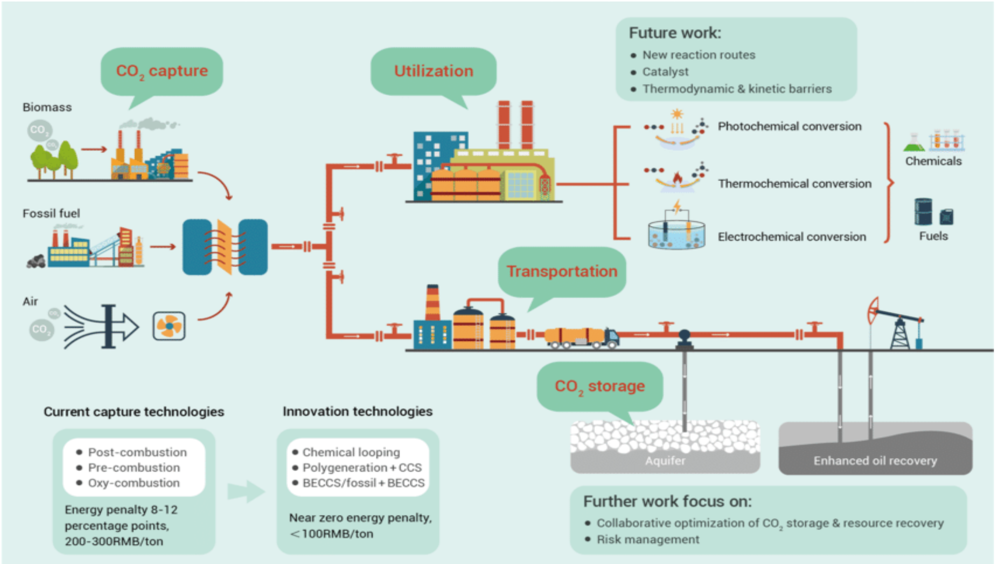

Figure 4. Roadmap for CO_2 utilisation in the GCC food industry

Figure 4 displays a CO_2 utilization roadmap for the GCC food industry, including short, medium, and long-term deployment timelines. Short-term strategies focus on high-TRL physical methods such beverage carbonation, MAP, refrigeration, cryogenic freezing, and fermentation CO_2 recovery. These applications are commercially viable, regulator-approved, and embedded in GCC food systems, decreasing emissions immediately through internal carbon reuse. For protein manufacturing, medium-term approaches include CO_2-derived packaging materials, methanol-based intermediates, and controlled microalgae culture. These methods fix more carbon but need process integration, energy optimization, and regulatory clarification. Electrochemical conversion, microbial lipid synthesis, and synthetic carbohydrates are transformational but low-TRL carbon-to-food technologies. The roadmap manages to address the technical maturity and GCC challenges such as energy intensity, water scarcity, and food security via incremental development steps. Linking the utilization pathways with deployment timelines, the image also manages speculative overreach, and it sets the stage for a comprehensive system which will gradually decarbonize the dry food system. The GCC food industry needs to transition from expedient short-term solutions to fundamentally transformative carbon-based food production models.

CO_2 consumption may simultaneously decrease productivity, enhance supply chains, and optimize resource efficiency in the GCC where agriculture is inextricably linked in terms of energy innovation, distillation, and industrial clusters. Therefore, this part provides a science-backed roadmap of CO_2 use in food with a focus on chemical, physical, and biological approaches with feasibility and reliability analysis studies in the GCC area.

Food System CO_2 Utilization Conceptual Framework

The CO_2 consumption pathways in the food business are defined by the degree of chemical transformation, carbon longevity, and energy requirements. Technology selection for GCC adoption is heavily influenced by energy costs, regulatory restraints, and food-grade purity standards.

- Direct usage of CO_2 without molecular modification is called physical utilization. These methods are low risk, commercially developed, and integrated into GCC food systems.
- Chemical utilization turns CO_2 into fuels, intermediates, or materials by catalytic or electrochemical methods. These techniques repair more carbon but demand more energy and system integration.
- Biological utilization aligns with circular economy concepts by converting CO_2 into biomass or food ingredients through microbial or photosynthetic mechanisms.

For the GCC food industry to effectively utilize CO_2, it is important to prioritize rapid physical routes and scale chemical and biological pathways for medium- to long-term transformation.

Physical Utilization Pathways: GCC Opportunities

Carbonation is the most common method of using CO_2 in the food sector. Demographics, urban lives, and climate have increased carbonated beverage demand in GCC countries including Saudi Arabia, UAE, and Qatar.

Table 4. Physical CO_2 utilization pathways in the GCC food industry

Physical utilization pathway	Food subsectors	Primary function of CO_2	Typical operating conditions	CO_2 demand level	Technology readiness (TRL)	Key benefits	Key limitations	GCC relevance
Beverage carbonation	Soft Drinks, sparkling water, malt beverages	Carbonation, mild preservation, sensory enhancement	Pressurized dissolution; low temperature	High	9	Mature technology; closed-loop recovery possible; food-grade purity	Limited to beverages	Very high – large beverage volumes and hot climate
Modified Atmosphere Packaging (MAP)	Meat, poultry, dairy, produce, bakery	Microbial inhibition; shelf-life extension	Elevated CO_2 (20–80%), reduced O_2	High	9	Chemical-free preservation; continuous CO_2 sink	Product-specific optimisation needed	Critical for long supply chains and imports
Controlled Atmosphere Storage (CAS)	Grains, fruits, vegetables	Respiration suppression; pest control	High CO_2, low O_2 environments	Medium	8–9	Long-term storage without fumigants	Infrastructure-intensive	Strategic for food security reserves
Refrigeration (CO_2-based systems)	Dairy, meat, frozen foods	Cooling and temperature control	Subcritical/transcritical CO_2 cycles	Medium	8–9	Zero ODP; high heat-transfer efficiency	High-pressure operation	Well-suited for high ambient temperatures
Cryogenic freezing (liquid/dry ice CO_2)	Seafood, meat, ready meals	Rapid freezing; quality preservation	Liquid/solid CO_2; cryogenic temperatures	Medium	8	Minimal ice-crystal damage; fast processing	CO_2 consumption cost	Valuable for frozen food exports
Inerting and blanketing	Oils, fats, powders, storage tanks	Oxygen displacement; oxidation prevention	Ambient pressure; gas-phase CO_2	Low–Medium	9	Simple implementation; low purity requirements	Indirect food contact	Useful for storage and oxidation-sensitive products
pH control via dissolved CO_2	Meat, beverages, enzyme-sensitive products	Mild acidification; enzyme suppression	Dissolved CO_2 → carbonic acid	Low	7–8	Reversible; additive-free	Limited pH range	Fits GCC preference for minimal additives

Physical utilization pathway	Food subsectors	Primary function of CO_2	Typical operating conditions	CO_2 demand level	Technology readiness (TRL)	Key benefits	Key limitations	GCC relevance
Dry ice for cold-chain logistics	Transport, emergency cooling	Temperature maintenance	Solid CO_2 sublimation	Medium	9	No residue; reliable cooling	Supply logistics	Highly relevant under extreme heat

Carbonation operations are good for receiving recovered CO_2 from fermentation or post-combustion capture units due to their high-purity CO_2 sink. Increasingly, beverage factories use CO_2 recovery systems to compress and reinject gas from bottling and filling into the carbonation loop. Beverage factories can achieve near-complete carbon circularity with upstream boiler or fermentation unit capture.

Modified Atmosphere Packaging (MAP) and Controlled Atmosphere Storage (CAS)

MAP and CAS are key CO_2 utilization methods in the GCC food sector, especially for meat, poultry, dairy, fruits, and vegetables. Under high ambient temperatures, these systems require raised CO_2 concentrations and reduced oxygen levels to suppress microbial development, delay ripening, and extend shelf life.

Long supply chains, import dependence, and the necessity to maintain food quality during storage and shipping make MAP and CAS essential in the GCC. Their CO_2 requirements are ceaseless and expectable; these technologies are appropriate for incorporated collection and recycle infrastructure in food processing hubs.

Refrigeration, Cryogenic Cooling, and Cold-Chain Applications

Refrigeration and cold chain logistics overcome in the GCC food industry, advancing a collaboration with CO_2 utilization. CO_2 is frequently consumed for:

- Prompt chilling during food processing,
- Temperature control during transport,
- Emergency cooling in cold-storage facilities.

Cryogenic CO_2 systems have advantages over traditional refrigerants, such as non-flammability, low toxicity, and food-grade compatibility. The carbon footprint of cold chain operations can be significantly reduced by utilizing CO2 from captured emissions rather than relying on imported industrial gas for refrigeration.

Chemical Utilization Pathways: From Process Gas to Food-Related Materials

Table 5. Pathways of chemical CO_2 use important to the GCC food sector

Chemical utilization pathway	CO_2 conversion route	Main products	Direct food use	Indirect food-system relevance	Energy demand	Technology readiness (TRL)	Key advantages	Key limitations	GCC relevance
CO_2-to-methanol (catalytic hydrogenation)	$CO_2 + H_2 \rightarrow CH_3OH$	Methanol	No	Feedstock for food-contact polymers, solvents, cleaning agents	High (H_2 + pressure)	7–8	Mature CCU route; scalable; integrates with green hydrogen	High energy demand; indirect food benefit	Strong synergy with GCC hydrogen strategies

Chemical utilization pathway	CO_2 conversion route	Main products	Direct food use	Indirect food-system relevance	Energy demand	Technology readiness (TRL)	Key advantages	Key limitations	GCC relevance
CO_2-to-dimethyl carbonate (DMC)	Catalytic conversion	DMC	No	Packaging polymers, coatings, food-contact materials	High	6–7	Low toxicity; versatile chemical	Complex synthesis; cost	Relevant for sustainable packaging
CO_2-derived polycarbonates	Copolymerization	Polycarbonates	No	Biodegradable or recyclable food packaging	Moderate–High	7	Long carbon retention; material substitution	Polymer processing required	Important for GCC packaging waste reduction
CO_2-to-organic acids	Electrochemical / catalytic	Formic, acetic acids	Limited	Preservatives, processing aids, intermediates	Moderate	5–6	Potential food-grade chemicals	Low TRL for food approval	Emerging long-term option
CO_2 mineralization for packaging fillers	Carbonation reactions	Carbonates	No	Fillers for paper/plastic packaging	Low–Moderate	7–8	Stable carbon storage; low risk	Indirect benefit only	Useful in local packaging industries
CO_2-to-syngas (RWGS)	Reverse water–gas shift	$CO + H_2$	No	Upstream feedstock for chemicals	High	6–7	Flexible platform chemistry	Multi-step process	Relevant for integrated industrial clusters
Electrochemical CO_2 reduction	$CO_2 \rightarrow C_1/C_2$ products	CO, ethanol, ethylene	No	Packaging, coatings, solvents	High (electricity)	4–6	Modular; renewable-powered	Low selectivity; cost	Long-term GCC decarbonization pathway

Renewable hydrogen production is a top priority for the GCC, and CO to methanol pathways can integrate energy transition and carbon utilization, which will indirectly benefit food manufacturing systems. Although chemical utilization pathway is more energy than physical reuse, they are essential for deep decarbonization since they may replace materials and fix carbon.

Biological Utilization Pathways: High-Value Carbon Assimilation

For the GCC food industry, biological CO_2 utilization through microalgae farming is a promising long-term approach. In arid regions, microalgae systems preserve water and land by carefully transforming CO_2 into biomass that is high in protein. Direct CO_2 feeding to photobioreactors to produce carbon negative proteins is made possible by integration with food processing or power generation facilities. Regional food security and protein diversity can be improved by processing biomass into food ingredients, animal feed, or nutraceuticals.

Engineering microbial systems like Ralstonia eutropha convert CO_2 into fatty acids, lipids, and other nutrition. These approaches demonstrate that direct carbon-to-food conversion can separate food production from agricultural land and freshwater constraints even at lower technology readiness.

Synthetic methods for CO_2-to-starch and CO_2-to-sugars expand food production options. Although limited to lab and pilot stages, these technologies foreshadow a future where carbon is the dominant caloric source, changing food systems.

Technology Readiness and GCC Feasibility Mapping

From a deployment perspective, CO_2 utilization pathways in the GCC can be broadly categorized as follows:

- **High TRL (Immediate deployment):** Carbonation, MAP/CAS, refrigeration, fermentation CO_2 recovery.
- **Medium TRL (Near-term scaling):** CO_2-derived packaging materials, methanol integration, controlled microalgae systems.
- **Low TRL (Long-term transformation):** Synthetic starch, microbial lipid synthesis, electrochemical food precursors.

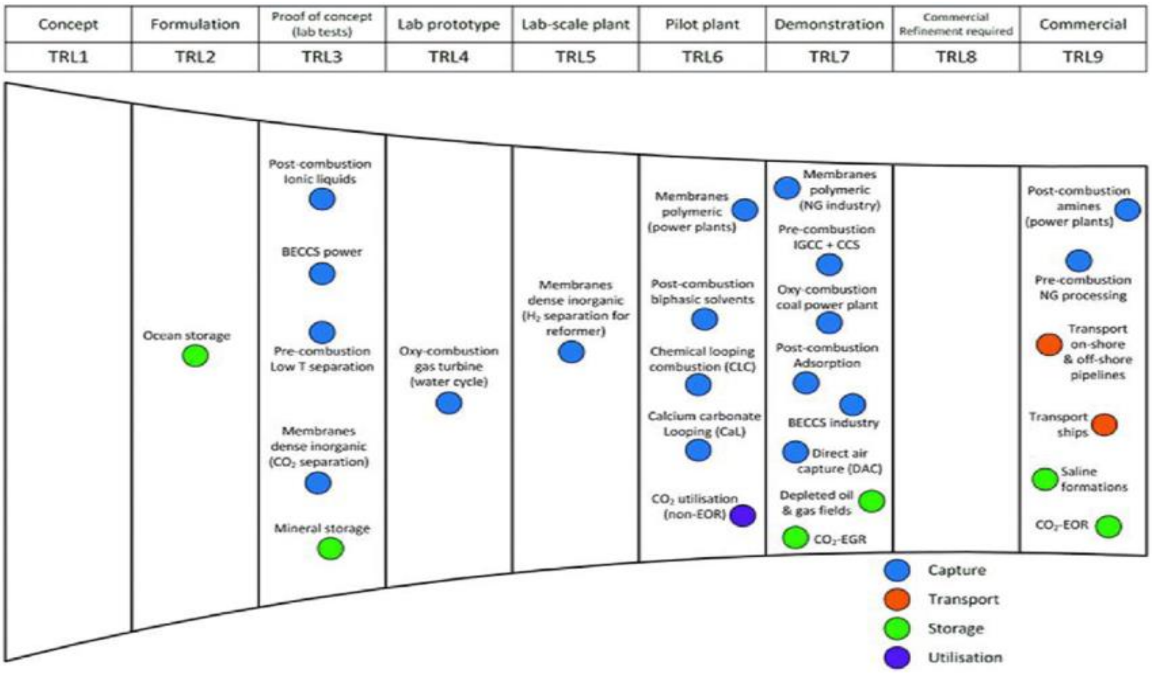

Figure 5. Technology readiness level (TRL) versus CO_2 uptake potential in GCC food systems

Figure 5 shows a bubble plot of food industry CO_2 use pathways versus technology readiness levels (TRLs). Bubble positions indicate application maturity, whereas size indicates CO_2 demand or deployment potential. Physical utilization pathways such carbonation, modified environment packing, refrigeration, and cryogenic freezing have the highest TRL, reflecting decades of industrial and regulatory acceptance. Methanol intermediates and `CO2 derived packaging are examples of chemical utilization processes that cluster around intermediate TRLs, suggesting pilot and early commercial scaling potential. Despite having low TRLs, biological and carbon to food pathways such as synthetic carbohydrates, microbial lipid synthesis, and algal protein production have important strategic ramifications for food security. The figure illustrates these reviews tiered deployment strategy, where mature applications reduce emissions while research and demonstration initiatives improve lower-TRL technology. It prevents speculative overstatement and gives reviewers a clear basis for assessing feasibility claims by separating maturity levels. (Hepburn et al., 2019; Fu et al., 2022).

Traditional Applications of CO_2

Before CCU became a climate mitigation framework, CO_2 was a crucial processing utility in the worldwide agricultural industry. These classical applications often disregarded in decarbonization discourse form the technological and operational underpinning for modern circular carbon initiatives. Traditional CO2 usage are crucial to food processing, preservation, and logistics in the GCC, where food production faces harsh climates and quality standards.

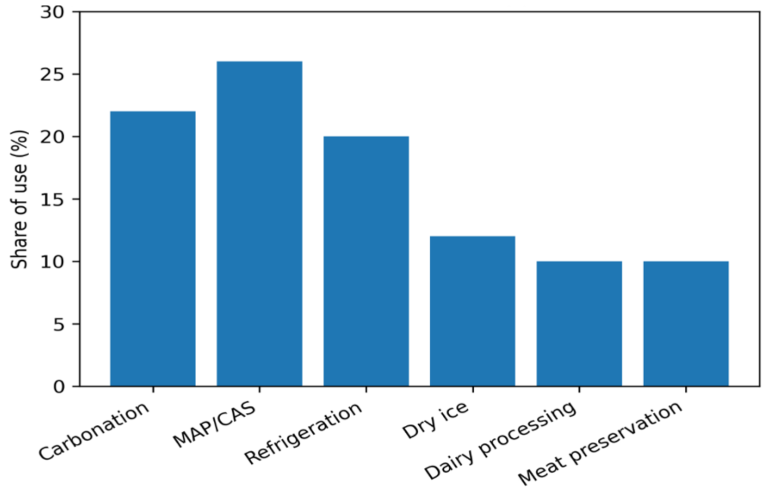

Figure 6. Distribution of functional CO_2 applications in GCC food processing

Figure 6 shows CO2 applications in GCC food processing procedures, such as carbonation, modified atmosphere packaging, cryogenic freezing, refrigeration, diary processing, and meat preservation. CO_2 demand in food systems is primarily from commercially established and vital applications. CCU's pragmatic benefits in the food business is that reuse paths match existing consumption patterns rather than creating new markets. The graphic shows that high CO2 usage subsectors, like drink, dairy, and cold chain logistics, also have high emission intensity, confirming the co-location of emission sources and reuse sinks. The main argument of the review that food systems are perfect for the implementation of circular carbon is supported by this alignment. (Kaliyan et al., 2007; Jayas & Jeyamkondan, 2002)

History of CO_2 in Food Processing

CO_2 is optimal for industrial applications owing to its physiochemical properties, which include colorlessness, odorlessness, chemical inertness, non-flammability, and ease of removal via depressurization or venting. Its antibacterial characteristics and phase change adaptability (gas, liquid, and solid) have resulted in its extensive application in the food sector. Food enterprises in arid and semi-arid regions, including the UAE, Qatar, Saudi Arabia, and Bahrain, have historically depended on CO_2 for product stability and prolongation of shelf life. Extended delivery pathways, severe weather, and imported foods intensify this need. Traditionally, food processing sourced CO_2 from industrial suppliers, typically as a byproduct of ammonia synthesis, hydrogen production, or petrochemical processes. Though this model of supply has functional value, it disjoints CO_2 use in the food field and its emission streams, neglecting internal carbon circularity.

CO_2 for Food Preservation and Shelf-Life Extension

Gas-Phase Preservation Mechanisms

The food industry's earliest use and extensive application of CO2 entails manipulating the atmosphere for preservation. Elevated CO_2 inhibits oxidative degradation, enzymatic activity, and aerobic microbial growth. For fresh vegetables, fish, cattle, and baked items, these effects are critical. In the GCC, CO_2 based preservation is essential since high temperatures hasten breakdown. Food loss and leftover are condensed when products are stored in CO_2 enriched environments because they have longer microbial lag phases, slower respiration rates, and delayed senescence.

Solid CO_2 (Dry Ice) in Transport and Storage

Food logistics has historically used solid CO_2, or dry ice for quick cooling and temperature maintenance. Dry ice is deal for frozen foods, seafoods, and pharmaceutical grade food since it sublimates without leaving liquid residue. During cold chain interruptions in GCC food supply chains, dry ice provides reliability due to vast transport distances and high exterior temperatures. Its conservative use generates a demand profile that can be met by captured and purified CO_2, decreasing the need for imported refrigerants.

CO_2 as a Functional Agent in Processing Operations

Inerting and Oxygen Displacement

In food processing and packaging, CO_2 is commonly utilized as an inert gas to substitute oxygen. Oxygen elimination reduces oxidation, stops aerobic bacteria growth, and retains sensory qualities. Standard operational preparation in processing units handling fats, oils, and oxidation perceptive materials is CO_2 blanketing. Inerting is a low-purity, uninterrupted procedure sink for CO_2 streams that may not exceed beverage grade criteria but are suitable for non-contact applications in carbon systems.

pH Control and Acidification

Carbonic acid is formed from dissolved CO_2, a restrained and changeable acidification reaction. This characteristic is used in food preparation to regulate pH without adding powerful acids that change flavors or regulation. CO based acidification is effective for meat processing, beverage stabilization, and enzyme control. Regulatory systems in the GCC prioritize food safety and additive reduction, making CO_2 a customer impartial alternative to chemical acidulants.

Refrigeration and Thermal Management

The usage of CO_2 in refrigeration systems predates modern environmental concerns. Supercritical and liquid CO2 refrigeration systems provide excellent heat transfer, are clean and environmentally friendly, and do not deplete ozone. They use CO2 preservation at food processing plants to cool down fast after heat treatment, provide emergency cooling if a system malfunctions, and achieve temperature control in fermented conditions. CO2 refrigeration units provide high stability at higher ambient temperatures than conventional refrigerants. These technologies are capable of carbon recycling and can back up food companies' local carbon economy via carbon capture infrastructure.

Conventional Applications as Portals to Enhanced Utilization

Traditional applications are suitable CCU deployment points in the GCC food industry due to these traits. Food processors can reduce emissions and prepare for higher value utilization by replacing externally generated CO_2 with internally captured streams.

Functional CO_2 Applications in the GCC Food Industry: Industrial Processes and Technological Advancements

Carbon dioxide is mostly used in the food sector for functional purpose. These uses are commercially regulator-accepted, mature, and integrated with GCC food processing infrastructures, unlike biological conversion or developing chemical approaches. Their widespread use and ability to rapidly absorb recovered CO_2 streams make them essential for a successful carbon circularity plan. Climate limits, tight food safety regulations, and lengthy logistical chains in the GCC exaggerate functional CO_2 applications. CO_2 is used as a process enabling agent, impacting product quality, safety, shelf life, and economic feasibility.

Carbonated Beverages

Carbonated beverages are most prominent and economically significant use of CO_2 in the food business. Due to high temperatures, and population growth, GCC soft drink, urban lifestyles, malt beverage, sparkling water, and carbonated dairy product consumption has extended continuously. In process engineering, carbonation involves dissolving CO_2 in aqueous solutions under pressure to create carbonic acid, which adds effervescence, taste and acidity. To maintain product consistency, CO_2 solubility must be precisely controlled based on temperature, beverage mix, and pressure. Carbonation is essential for preservation beyond taste. Dissolved CO_2 lowers oxygen availability, limits soilage microbial growth and suppresses yeast and mold activity. Carbonation increases microbiological safety during distribution and storage in GCC food systems, where severe heat can disrupt cold chains.

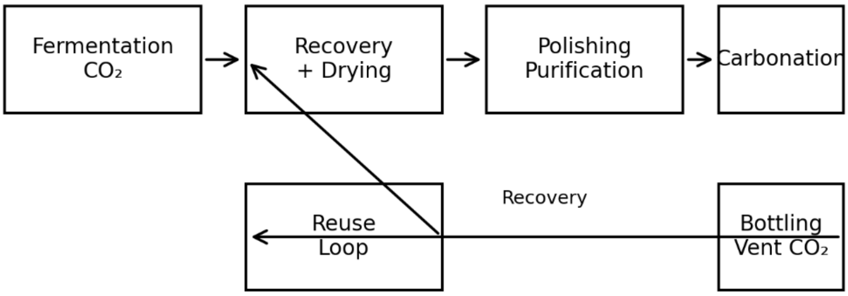

Figure 7. Closed-loop beverage carbonation system using captured CO_2

Figure 7 shows a closed loop carbonation system that recycles CO_2 from fermentation and bottling for beverage carbonation. It also illustrates near zero waste CO_2 loops in beverage facilities using impurity reduction, gas recovery, compression, and reinjection. The technology enhances supply security, lowers operating costs, and minimizes emissions by reducing import of industrial CO_2. This statistic supports the review's focus on process-integrated CCU solutions with immediate economic and environmental advantages (Kaliyan et al., 2007; Jain, 2025).

CO_2 recovery systems are used in beverage industries to catch gas during bottling and filling. Upstream collection from fermentation or boiler exhausts enables closed-loop carbonation, reducing industrial CO_2 and carbon intensity.

Modified Atmosphere Packaging (MAP) and Controlled Atmosphere Storage (CAS)

CO_2-based technology such as Modified Atmosphere Packaging (MAP) and Controlled Atmosphere Storage (CAS) is crucial in the GCC food industry. Systems that alter gaseous composition around food goods, such as increasing CO_2 concentration and reducing oxygen levels, suppress microbial growth, delay enzymatic activity, and slow respiration.

MAP in Fresh and Processed Foods

Meat, poultry, seafood, fresh vegetables, bakery, and ready-to-eat meals use MAP widely. Increased CO_2 levels hinder aerobic spoilage, while oxygen reduction restricts oxidative deterioration. MAP can increase shelf life by an order of magnitude in high-protein foods.

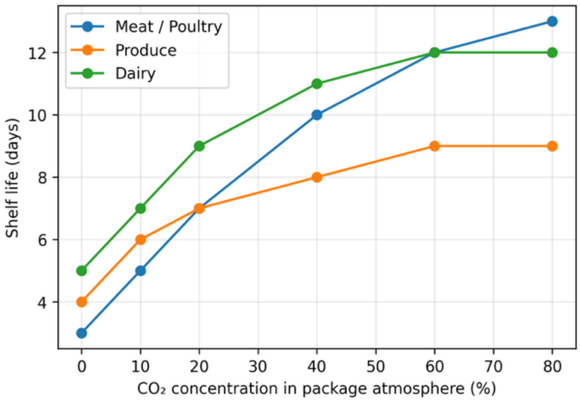

Figure 8. MAP effectiveness under GCC climatic conditions

Figure 8 shows the correlation between CO_2 levels in modified atmosphere packaging (MAP) and food shelf-life extension in the GCC's high ambient temperature. High CO_2 levels at temperatures over 35-40 °C mitigate microbiological development, oxidative damage, and enzymatic breakdown, extending shelf life. In meat, poultry, dairy, and fresh produce, CO_2-rich atmospheres greatly reduce respiration and microbial activity. The graphic demonstrates GCC food supply systems using structural MAP for long-distance transit and preservative-free storage. Internal carbon reuse systems require MAP as a stable food-grade CO_2 sink. Optimise product-specific gas composition for microbial suppression and sensory and textural quality. To optimize MAP-based CCU routes in arid locations, analyze the relationship between preservation performance and CO_2 concentration in GCC conditions. Research shows that CO_2 preserves and cycles carbon resources (Jayas & Jeyamkondan, 2002; Lee, 2016; Zhang et al., 2015). MAP aids in preserving imported and domestically processed goods in severe GCC climates. MAP systems efficiently extract food-grade CO_2 due to their predictable demand.

CAS in Bulk Storage and Grain Preservation

Controlled Atmosphere Storage applies MAP to large-scale grain, fruit, and vegetable storage. High CO_2 levels harm insect metabolism, hinder fungal growth, and minimize post-harvest losses without chemical fumigants. GCC nations that import grains and strategic food stockpiles can use chemical-free CAS systems for food security. Combining CAS with on-site CO_2 capture can dramatically lower the carbon footprint of long-term food storage.

Inactivation of Microorganisms

CO_2 has outstanding antibacterial effects, specifically at high pressure or attentiveness. Intracellular acidification, enzyme inhibition, membrane disruption, and metabolic interference contribute to its efficacy.

High-Pressure CO_2 Processing

High pressure CO_2 ($HPCO_2$) is a non-thermal decontamination technique that maintains sensory and nutritional integrity while disregarding yeasts, bacteria, and moulds. This technique is optimal for temperature sensitive products such as diary, liquids, and prepared meals. HPCO2 serves as a feasible substitute for heat sterilization in the GCC, where customer demand for minimally processed products is increasing. Integrating it into production lines can energy usage and utilize CO_2.

Synergistic Preservation Systems

To increase microbial inactivation, CO2 is often combined with mild heat, essential oils or ethanol vapour. As premium food markets in the GCC requires lower processing intensities, these synergistic systems reduce energy use and preserve product quality.

Inactivation of Enzymes

Food damages, loses quality, and discolors due to enzymes. CO_2 based enzyme inactivation offers a non-chemical, reversible option to acidification or heat treatments. In watery food matrices, CO_2 lowers pH and alters enzyme's structure, reducing catalytic activity. Lipase inhibition in dairy and meat products, fruits and vegetable browning management, and oil and fat oxidative stability have been achieved. High temperatures accelerate GCC food processing enzymatic degradation. CO_2-mediated enzyme control enhances preservation beyond refrigeration and packaging.

CO_2 in Slaughtering and Meat Preservation

CO_2 serves both animal welfare and product quality goals in meat production. Before slaughter, controlled CO_2 stunning induces unconsciousness, lowering stress reactions that impact meat texture, color, and water-holding ability. After slaughter, CO_2 enriched atmosphere will prevent decay and increase shelf time of the fresh and processed beef products. CO_2 based preservation is critical for food safety practice in the GCC, with a focus on meat consumption and the need for temperature stability throughout the food chain.

Refrigeration Systems

CO_2 based refrigeration solutions are considered as an environmentally friendly alternative to conventional options. It offers excellent heat transfer efficiencies, no ozone depletion, and food grade compatibility at transcortical or subcritical temperatures. There are robust CO_2 refrigeration systems that work.

Cryogenic Freezing in the Global Frozen Food Industry

Cryogenic freezing of liquid or solid CO_2 can significantly lower temperature in a controlled manner using liquid or solid CO_2 which reduces the freezing temperature and thus can stop the formation of ice crystals for preservation of cellular integrity. This method is used for seafood, vegetables, meat, as well as cooked meals. Convenience and food security are focal points for the GCC frozen food industry where the product quality sustains through long storage and movement with cryogenic CO_2 freezing. The use of obtained cryogenic CO_2 is significantly a means for reducing the carbon footprint resulting from frozen food production.

Dairy Technology

Dairy industry consumes a ration of CO_2 because they comply with cleanliness rules and rely on cold chain logistics. In dairy production, CO_2 is used to treat spoilage bacteria, prolong the milk shelf life, improve the stability of the butter and yoghurt, and improve cheese production. However, due to the difficult environment of dairy industry in GCC region, CO_2 is effectively used to manage microorganisms because waste is significantly reduced, thereby helping in better and more efficient production in all aspects of dairy supply chain. On-site CO_2 recovery equipment could be adopted in dairy operations to increase circular carbon consumption.

Turning Carbon into Calories

Converting CO_2 directly into calories is a revolutionary breakthrough in food science and sustainable engineering. Consequently, biological and synthetic techniques convert CO_2 into liquids, proteins and food components, thus liberating food crops and carbohydrates from traditional limitations. For GCC countries marked by limited land for arable varieties, arid conditions, and significant dependency on food imports, these technologies constitute a strategic entry point for climate-resilient, land independent food production. Here is the spotlight on the most promising pathways for converting carbon to food, emphasizing their scientific basis, technological evolution, and importance to the GCC's energy water food nexus.

Microalgae Protein Systems

Food systems based upon the biomass of microalgae are a high-quality scalable technology to process CO_2 into biomass rich in nutrients. Microalgae use photosynthesis to produce higher amounts of proteins, carbohydrates, fats and micronutrients in CO_2 as a reaction of production than terrestrial crops can.

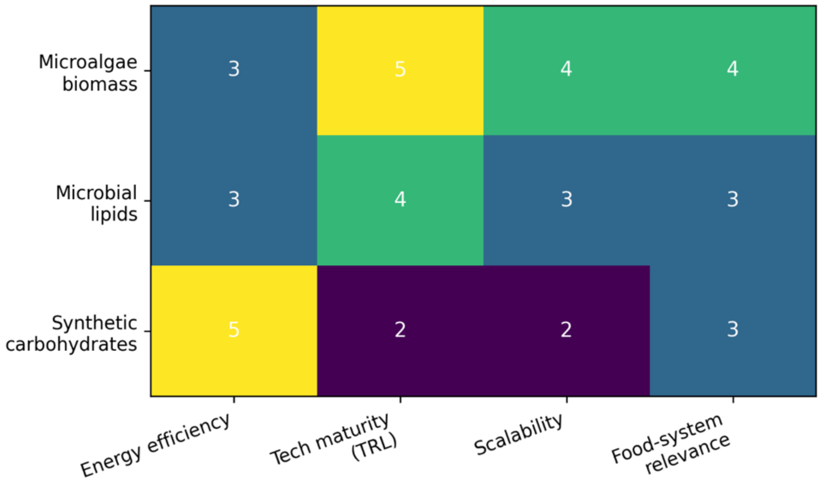

Figure 9. Comparison of emerging carbon-to-calorie pathways

Figure 9 illustrates carbon-to-calorie processes such as microalgae biomass, microbial lipid synthesis, and synthetic carbohydrate production. Evaluate energy efficiency, technological maturity, scalability, and significance within the food system. Synthetic pathways are laboratory-scale yet theoretically more efficient. Biological systems govern short-term vitality. To prevent exaggerating preparedness and emphasize enduring transformative opportunities for GCC food systems, the figure juxtaposes innovative potential with practical limitations (Cai et al., 2021; Wang, 2022).

Process and Metabolism

In optimum conditions, some microalgal species can produce 60–70% protein of dry biomass, outperforming soy, legumes, and animal-derived proteins. For areas with limited agricultural capacity, microalgae photosynthetic carbon fixation has higher areal productivity and shorter growth cycles than land-based crops. GCC closed photobioreactor systems offer superior control over temperature, light intensity, fertilizer supply, and CO_2 content compared to open ponds. Deserts need this technology to reduce evaporation and pollution.

Industrial CO_2 Source Integration

Supplying CO_2 from food-processing, electricity, or desalination plants directly to photobioreactors turns industrial emissions into food-grade biomass. Emissions sources and food producers minimize net emissions and boost protein security. Microalgae farming, grounded in the systems engineering, aligns with the GCC's industrial clustering biomass production, carbon capture, and food processing.

Synthetic Pathways for Ralstonia Eutropha CO_2-to-Fatty Acid Conversion

Chemoautotrophic bacteria like Ralstonia eutropha can convert CO_2 into valuable lipids and fatty acids necessary for human sustenance and food production, unlike photosynthetic species.

Microbial Carbon Fixation and Lipid Biosynthesis

Metabolic engineering optimizes pathway lipid synthesis to augment fatty acid production. Genetic modifications greatly increased the generation of free fatty acids, thus enabling the establishment of microbial lipid factories. These lipids can help in the synthesis of nutraceuticals, important food additives, and edible oils. Microbial systems offer regulated independence from sunlight for regions facing solar intermittency or scarce land use.

Significance of the GCC Food–Energy Nexus

Recent high-velocity developments in green hydrogen investment in the GCC make Ralstonia eutropha-based systems feasible. These microbial systems transform waste from the energy industry into edible lipids with renewable hydrogen and CO_2 to serve as a link between energy and food. Technical readiness is moderate, although it's expected that improvements in design of reactors, the optimization of bioprocesses and flexibility of strain adaptation will ensure future scale and economics in the next 10 years.

High-Efficiency Synthetic Approach for CO_2-to-Starch Conversion

Resent advances in synthetic biology and chemoenzymatic systems enable non-natural conversion of CO_2 into starch, a vital caloric source. These systems use modular reaction cascades for CO_2 reduction and enzyme-mediated polymerization.

Enzymatic Carbon Fixation

Synthetic starch production processes avoid plant metabolism inefficiencies, unlike photosynthesis. These systems generate greater conversion efficiencies per unit of energy input by directly converting CO_2 and hydrogen into glucose intermediates and polymerizing them into starch. Synthetic starch can be used in food formulations, thickeners, and processed items because structural investigations show it is chemically and functionally identical to plant-derived starch.

Food Security Implications

Synthetic starch synthesis is a disruptive technology that could reduce GCC cereal imports. Although yet in lab and pilot stages, such systems show that staple carbs can be made from carbon, water, and renewable energy alone.

Carbon-to-Food Technologies Wider Impact

Carbon-to-calorie technologies transform food production by: Decoupling supply from land and water availability, creating nutritional resources from industrial CO_2 emissions, increasing resilience to climate variability and supply-chain disruptions. Large-scale implementation faces scale-up, cost, energy efficiency, regulatory approval, and consumer acceptance issues. Pilot-scale facilities connected with industrial centers, supported by legislative incentives and public–private partnerships, will likely drive early adoption throughout the GCC.

Patent-Based Analysis of CO_2 Utilization

Patent analysis assesses the technological maturity, commercial aim, and innovation trajectory of CO_2 usage in food. Unlike academic journals, patents suggest near-market readiness, proprietary engineering solutions, and strategic industry investments. A patent-based strategy is essential for evaluating CO_2 reuse pathways in the GCC food industry. Over the past 20 years, CO_2 utilization patents have increased due to climate policies, circular economy, and capture/conversion technology improvements. Utilizing CO_2 in food requires rigorous purity requirements, regulatory control, and process integration over conversion.

Table 6. Patent landscape summary for CO_2 reuse technologies in the food industry

Application domain	Representative IPC classes	Typical assignees	Patent activity level	Technology maturity signal	Commercialisation status	Key innovation themes	GCC relevance
Modified Atmosphere Packaging (MAP) & preservation	B65D, A23B, C12N	Multinational packaging firms; food processors	High	Mature, incremental innovation	Commercial	Gas composition optimization; package design; shelf-life control	Very high – core GCC cold-chain need
Beverage carbonation & CO_2 recovery	C12G, A23L, B01D	Beverage multinationals; equipment suppliers	High	Mature, process-integrated	Commercial	CO_2 recovery during bottling; impurity removal; closed loops	Very high – large GCC beverage volumes
Refrigeration & cryogenic cooling	F25B, F25C	Refrigeration OEMs	Medium	Commercial but evolving	Commercial	Transcritical CO_2 systems; efficiency at high ambient T	High – suited to GCC climate
Dairy & fermentation systems	A23C, C12C	Dairy processors; biotech firms	Medium	Pilot–commercial	Early commercial	Fermentation gas recovery; microbial control	High – expanding GCC dairy sector
Food-grade CO_2 purification	B01D, B01J	Gas technology companies	Medium	Commercial	Commercial	Trace impurity removal; food-grade compliance	Critical enabling technology
Biomass & single-cell protein (SCP)	C12N, C12P	Biotech startups; research institutes	Low–Medium	Early-stage innovation	Pilot	Microalgae reactors; gas-to-biomass integration	Medium – pilot opportunities
CO_2-derived packaging materials	C08G, C08L	Chemical companies	Medium	Pilot–early commercial	Pilot	Polycarbonates; bio-based polymers	Medium – packaging sustainability
Carbon-to-food (synthetic carbs, lipids)	C12P, C07C	Academic–industry consortia	Low	Exploratory	Lab–pilot	Synthetic pathways; enzyme cascades	Long-term GCC innovation niche

Scope and Methodology of Patent Landscape Assessment

Major worldwide databases, such as the World Intellectual Property Organization (WIPO), the European Patent Office (EPO-Espacenet), the United States Patent and Trademark Office (USPTO), and Google Patents, are used in the patent analysis that forms the basis of this assessment.

Keyword combinations such carbon dioxide utilization, food processing, carbonation, modified atmosphere packaging, CO2 fermentation, food preservation, and biogenic carbon reuse were the focus of search techniques. To find patent families that directly applied to food and beverage systems, energy-only or non-food chemical routes were eliminated unless they showed a definite downstream significance.

Application domain (food preservation, beverages, biomass growth, packaging), utilization mechanism (physical, chemical, and biological), technology readiness indicators, and relevance to GCC industrial settings were the criteria used to categorize patents.

Global Patent Trends in CO2 Utilization in the Food Sector

- Most patents in the food industry for CO_2 innovation involve physical use methods. Carbonation, modified environment packaging, refrigeration, and microbiological control are examples. Physical techniques prevail because to low regulatory risk, technical maturity, and fast market need. A small but growing area, chemical utilization patents cover CO_2-derived food-grade chemicals, organic acids, and packaging polymers. Patents for process intensification, catalyst selectivity, and energy integration suggest lab-to-pilot-scale deployment. The creative biological utilization patents involve microalgae, single-cell protein, and microbial conversion. Although rare, these patents have high citation rates, indicating scientific and commercial interest. Many prioritize closed-loop CO_2 capture and biomass cropping options to achieve circular economy aims.

CO_2 Utilization Distribution Patents

- Patent classification ranks food industries:

1. *Food storage and prolonging life:* MAP, CAS, and microbial inhibition technologies dominate patent filings, demonstrating the importance of food preservation in hot climes.
2. *Carbonating beverages and recovering gas*: Patents in this area emphasize CO_2 recovery during bottling, pressure optimization, and integration with fermentation exhaust streams.
3. *Dairy and fermented:* Innovations in CO_2-rich environments focus on microbial control, enzyme inhibition, and oxygen management.
4. *Protein alternatives, biomass growth:* This category comprises microalgae cultivation, photobioreactors, and microbial fermentation platforms that use collected CO_2.
5. *Packaging and materials:* New patents encompass CO_2-derived polymers, carbonates, and biodegradable food-contact materials.

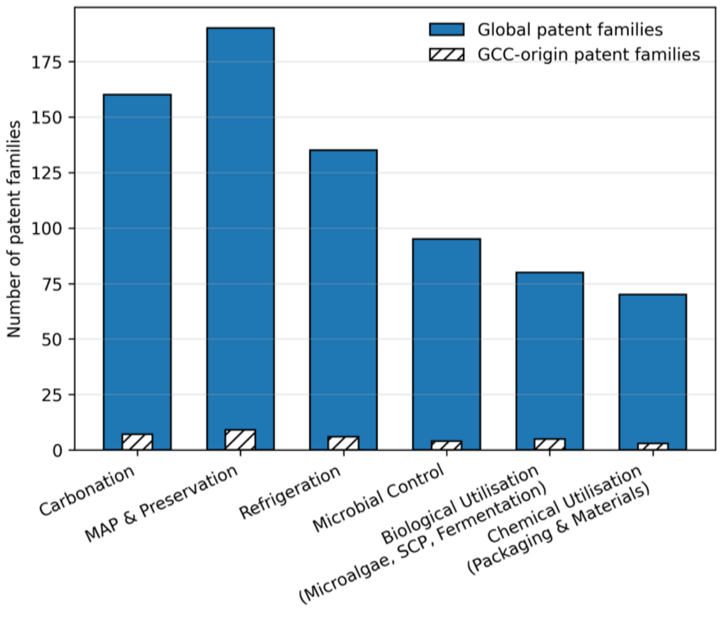

Figure 10. Patent landscape of CO_2 reuse technologies in the food industry

Figure 10 illustrates the food industry's CO_2 reuse patent landscape by application and technology. Carbonation, modified environment packing, refrigeration, and microbiological control dominate patent clusters, indicating commercial maturity and regulatory acceptability. Microbial fermentation, single-cell protein production, and microalgae cultivation are emerging biological utilization clusters with high innovation intensity but low absolute patent counts, indicating long term strategic interest. Sustainability and circular economy policies are driving the growth of chemical usage routes, including CO_2-derived materials and food packaging intermediates. GCC assignees have few patents, suggesting that adaption is more important than creation. A graphic showing patent density and technological focus supports the review's argument that upgrading and integrating current technologies has near-term influence and investing in biological leads to long-term leadership (Jain et al., 2025; WIPO, 2024)

GCC Position in the Global Patent Landscape

Despise its industrial strength, the GCC holds a modest share of global food-sector CO_2 utilization patents. Most GCC filings include application implementation, not process invention. Not weakness, this division offers strategic opportunity. Saudi Arabia and UAE are investing in food tech centers, alternative protein, industrial decarbonization carbon management infrastructure, and controlled environment agriculture Through our investments, we promote localized innovation in scale-up engineering, process integration, and climate-specific CO_2 usage solutions.

Strategic Patent Trends

Patent analysis facilitates the decarbonization of the GCC food chain. Optimization, rather than invectiveness, yield immediate effects; retrofitting food production facilities with CO_2 recovery and reuse systems reduces emissions more rapidly than the introduction of novel chemicals.

- Pure food sets you apart: Patent strengths include purification, contamination control, and regulation.
- Integration beats isolation: Patents with strong commercial signals capture, use, and process products.
- Biological pathways disrupt long-term: Recent biomass-based patents suggest GCC-sustainable food production.

Technological Insights from the Patent Domain

This section analysis exemplary patent families to underscore the significance of CO_2 in food systems beyond aggregate trends. The images demonstrate engineering logic, problem solution framing, and GCC deployment relevance.

Table 7. Gap analysis and research priorities for CO_2 reuse in the GCC food industry

Domain	Current state (literature & practice)	Identified gap	Why this gap matters in the GCC	Priority research / implementation actions
Food-sector CO_2 emissions inventory	Global or regional averages used	Lack of GCC plant- and subsector-specific CO_2 inventories	GCC food systems have extreme cooling demand and import dependence; global averages misrepresent reality	Develop plant-level CO_2 audits by subsector (dairy, beverages, meat, frozen foods, cold chain)
CO_2 source purity characterization	Capture sources broadly described	Missing quantified impurity profiles for GCC food-plant CO_2 streams	Food-grade reuse depends on ppm-level contaminants; GCC industrial adjacency increases risk	Establish CO_2 quality databases (fermentation vs flue gas vs hybrid sources)
Food-grade CO_2 regulations for captured CO_2	Conventional food-grade CO_2 standards exist	No explicit regulatory guidance for	Regulatory ambiguity delays investment and scale-up	Develop tiered GCC standards by application (direct

Domain	**Current state (literature & practice)**	**Identified gap**	**Why this gap matters in the GCC**	**Priority research / implementation actions**
		"captured CO_2" reuse in food		contact vs indirect use)
Techno-economic analysis (TEA)	CCU TEAs exist for energy/chemicals	Limited food-specific, GCC-context TEA	Energy pricing, subsidies, and CO_2 logistics differ in GCC	Conduct scenario-based TEA including energy prices, carbon credits, CO_2 price volatility
Life-cycle assessment (LCA)	LCA applied unevenly	Physical reuse pathways often excluded or oversimplified	Reuse can increase emissions if energy penalty is ignored	Perform system-boundary LCAs for MAP, refrigeration, carbonation
Cold-chain system integration	Fragmented solutions	No integrated CO_2 cold-chain hub designs	Cold-chain is the largest GCC food emission driver	Design CO_2 hubs supplying MAP, dry ice, refrigeration
MAP/CAS optimization for hot climates	MAP widely applied	Limited GCC-specific MAP gas recipes and models	Shelf-life behavior differs under extreme heat	Develop product-specific MAP matrices for GCC logistics
Dairy and beverage case studies	Mostly non-GCC case studies	Lack of demonstration plants in GCC	Reviewers demand real-world validation	Implement pilot CCU loops in GCC dairy and beverage plants
Chemical CCU linkage to food systems	Methanol and polymers studied	Weak articulation of food-system relevance	Reviewers question "why chemical CCU belongs here"	Map CO_2 → chemicals → packaging → food contact value chains
Biological CO_2 utilisation (microalgae, SCP)	Lab–pilot scale globally	Few GCC-adapted reactor designs	Heat, water, and salinity constrain performance	Develop closed reactors, saline strains, desalination coupling
Carbon-to-food (synthetic carbs, lipids)	Proof-of-concept only	No scale-up or regulatory pathway	High risk of over-speculation	Position as long-term, with milestone-based roadmap
Patent localization	Global patent dominance	Low GCC-origin patent activity	Missed opportunity for regional innovation	Encourage local IP generation in purification, MAP systems
Public perception and acceptance	Limited consumer studies	No GCC-specific perception data	Food acceptance is culturally sensitive	Conduct consumer trust and labeling studies
Governance and implementation pathways	CCU roadmaps exist	No food-sector-specific GCC playbook	Without governance, CCU remains pilot-scale	Develop phased deployment frameworks with MRV metrics

Flue Gas CO_2 Capture and Integrated Microalgae Cultivation

Many patents combine CO_2 extraction with microalgae production, typically using flue gas as the carbon source. CO_2 is collected through aqueous absorption, frequently with ammonia, and then released into photobioreactors under controlled conditions. The invention, process integration, turns waste emissions into biomass without compression or long-distance transfer. The GCC benefits from co-locating these systems with food processing, power, and desalination plants. Translating emissions into nutritional and economic value, production with protein-rich biomass or feed additives from these systems boost food security.

Beverage Production Captured CO_2 Streams

A prominent patent cluster includes the use of CO_2 as a substitute for external gas in the carbonation of beverages. These advances include the elimination of trace contaminants, foaming and oxidation control, and carbonation pressure stability. The patents demonstrate that food grade CO_2 can be reused, provided the level of purification and quality assurance required is adequate. GCC beverage facilities have internal carbon loop systems that reduce both emissions and costs.

Clean CO_2 Feedstock for Food-Related Chemicals

Carbon dioxide is also transformed into organic carbonates, acids, and intermediates for utilization in food processing and packaging under a third patent category. Applications such as energy efficient catalytic methods, industrial product integration, and hazardous waste reduction are also commonly patentable. These technologies indirectly lower carbon emissions by replacing dietary ingredients produced from fossil fuels.

GCC Food Industry Deployment Lessons

Addressing issues, connecting with current infrastructure, and providing co-benefits including waste reduction, cost savings, and improved product quality are all components of effective CO_2 revalorization strategies.

Barriers to the GCC Food Industry's Adoption of Carbon Capture, Utilization, and Storage: Public Perception, Policy, and Technology

Food industries, particularly those in the GCC, are sluggish to adopt carbon capture, utilization, and storage (CCUS) technology despite its economic significance and technical maturity. Although there are advantages to CO_2 reuse in the food industry, such as the need for food-grade carbon dioxide and process integration, its broad usage is constrained by structural, legal, financial, and social factors. It is possible to develop practical decarbonization strategies and avoid extending laboratory or pilot-scale accomplishments to commercial food systems by being aware of these difficulties.

Technological Obstacles

Process and Energy Efficiency

To capture, purify, and compress CO_2, CCUS systems need a lot of energy. Energy penalties can swiftly harm the economic viability of the food processing industry because its margins are lower than those of the petrochemical or energy sectors. Physical channels (MAP, carbonation, refrigeration) use less energy than chemical and biological processes, which may involve high-pressure operation, hydrogen or nutritional inputs, catalytic or electrochemical conversion, and rigorous downstream separation.

For energy-intensive CCU routes to be adopted in the GCC, where power prices are becoming more regulated and efficiency is being benchmarked, they must demonstrate system-level benefits such waste heat recovery, renewable energy integration, or material displacement.

CO2 Purity Standards for Food-Grade

Unlike the energy or construction industries, the food business is subject to stricter CO2 purity rules for direct-contact applications. Food safety, flavor, and compliance can be jeopardized by sulfur compounds, nitrogen oxides, hydrocarbons, and leftover solvents. Many purification steps are usually required to capture CO_2 from combustion or industrial exhaust streams, increasing the initial and ongoing expenditures. Not all food processing facilities may have access to fermentation-derived CO_2 streams, even though they are cleaner.

While lower-purity reuse (inerting, refrigeration) is underutilized because of conservative operating procedures, higher-purity reuse (carbonation, MAP) needs improved purification. To bridge this gap, food-sector certification and improved application-specific purity criteria are required.

Scale Mismatch and Infrastructure Integration

Typically, CCU technologies are created at insufficient scales for food processing. Distributed food processing facilities might not benefit from large, centralized capture systems, while small modular units might not scale well.

Shared CO_2 infrastructure has potential in the GCC, where industrial zones dominate food production. Long-term supply agreements, standardized interfaces, and stakeholder participation are not common.

Market and Economic Obstacles

Operating and Capital Expenses

CCUS implementation in the food business is hindered by high beginning costs. Compared to heavy sectors, food processors invest less. CCU projects find it difficult to satisfy IRR requirements in the absence of carbon pricing, subsidies, tax breaks, or preferred financing for low-carbon technologies. CCU suffers economically from energy subsidies in GCC economies. But investment logic is evolving in response to changing subsidies and net-zero pledges for export-oriented food companies — including international carbon disclosure regulations that need to be upheld.

Market Uncertainty for CO-Derived Products.

Market Uncertainty for CO-Derived Products

Inadequate insight of food additives prepared from CO_2 towards the market cost, acceptability, and regulatory approval is affecting the chemical and biological utilization. Although CO-derived lipids, proteins, and carbohydrates have sustainability benefits, their commercial viability depends on a high level of consumer trust, regulatory approval, and competitive pricing. In the wide and culturally aware GCC food industry, new carbon-based foods need to be accessible and positioned properly.

Barriers to Policy and Regulation

Disjointed Rules

In an environment with inconsistent CO_2 reuse regulations CCUS is hard to enforce in the food industry. Existing permitted additives and processing aids are delineated, yet food safety codes may not permit the reuse of captured CO_2 as a feedstock. Regulatory ambiguities discourage food companies from investing in technically viable alternatives. Applications for CCU food applications in the GCC are rare and the laws are subject to constant changes.

The Recognition Gap in Carbon Accounting

Many applications of carbon capture and utilization (especially physical reuse) have been overlooked by national carbon accounting frameworks. Companies that use CO_2 do not earn emission reduction certificates. Addressing carbon reuse criteria to national greenhouse gas inventories and corporate reporting standards could increase the food industry's attractiveness to CCU investments.

Acknowledgement and Societal Perception

Concerns and Hazards for Consumers

A difficult, albeit significant challenge to the adoption of CCU in the food chain is social acceptance. Even though CO_2 is a naturally occurring substance in beverages and preservation systems, the concept of captured carbon entering the food chain may trigger worries about safety, artificiality, and environmental integrity. Although not scientifically rigorous, these theories are influential and affect market outcomes a good deal. Clear communication and regulatory recognition are essential in this regard. But GCC nations place great emphasis upon food safety, quality, and adherence to religious standards, so such requirements can only be met through official endorsement.

Certification, Labeling, and Trust

Explicit certification, independent safety assessments, and transparent labeling are vital for increasing consumer confidence in CO2 derived food products. Without such initiatives, technically sound and environmentally friendly technology can be met with resistance.

Enabler Obstacles

Significant but doable obstacles stand in the way of CCUS adoption in the GCC food sector. Governance, coordination, and perception management are just as crucial as engineering innovation because most barriers are institutional rather than technological. Targeted legislative incentives, food-grade CO_2 requirements, integration of the national net-zero roadmap, public engagement, education, and pilot-scale demonstration projects in food-processing hubs are the factors that facilitate CCU in the food industry.

Prospects and Policy Directions for CO2 Reuse in the GCC Food Sector

Successfully integrating CO_2 reuse in the GCC food business involves technological readiness, policy frameworks, institutional alignment, and strategic planning. As GCC countries work toward net-zero targets and diversify from hydrocarbons, the agricultural sector presents a high-impact, low-regret opportunity to scale up circular carbon approaches.

GCC Food Sector Strategic Importance

GCC food system decarbonization plans address energy, water, climate, and societal stability specifically. Food production affects public health, making decarbonization politically and socially sensitive. High usage of refrigeration, desalinated water, imported supplies, and fossil-based electricity makes the sector carbon-intensive. Regard CO_2 reuse as a strategic instrument to bolster food system resilience, rather than solely for emission reduction. Implementation of carbon circulatory in food processing, packaging and preservation will serve to lower the dependence on imported industrial CO_2, reduce life cycle emissions, enhance conformance to global carbon disclosure and sustainability standards, and advance food security in GCC countries facing climate threats. In terms of circular economy, industrial decarbonization, and food technology Saudi Arabia and UAE have both a lot of ambition. The re-use of CO_2 in the food sector supports these goals as well and may motivate the introduction of carbon capture and utilization (CCU).

Boosting CO-Reuse Adoption Policy Instruments

Regulatory Clarity and Food-Grade CO_2 Standards

Explicit recommendation on regulations on which food grade CO_2 derived from collected sources is controlled shall be provided. Food safety rules sometimes require purity standards for carbonation, modified atmosphere packaging (MAP), refrigeration, and biological conversion to mitigate ambiguity and speed the industry's adoption. It would promote regional food trade and integration to have unified GCC legislation.

Economic Incentives and Risk-Sharing

To cut down capital requirements, governments can provide incentives such as grants for retrofit costs in food processing plants for carbon capture and utilization, preferential tariffs or tax exemptions for CO_2 reutilization equipment, green finance options, or carbon credit or offset solutions that cover CO_2 reuse. Policy supported demand signals will enable technical and economic feasibility in a domain free from carbon price.

Industrial Clustering and Integration

The GCC's industrial structure, marked by centralized logistics, shared utilities, and a concentration of industrial zones, has a big impact on CO_2 reutilization. The proximity of food processing factories near energy, petrochemical, and desalination facilities the common infrastructure for CO_2 collection, purification, and distribution. The forthcoming strategy must augment CO_2 hubs for food procedures, include food procedures, include food sector carbon capture and utilization systems into industrial symbiosis projects, and co-locate capture, utilization, and renewable energy.

Clustering reduces unit costs, improves reliability, and allows scale-up without burdening food producers.

Innovating, Demonstrating, Scaling

Some CO_2 reuse applications in the food industry are commercially viable, while others, such as biological and synthetic food channels, are currently being studied. Public pilot and demonstration projects must validate performance in GCC climates to close this gap. Develop local operational competence. Assess food safety and regulatory compliance Gain consumer and investor trust.

Incubators, public–private partnerships, and government-backed food-tech innovation programs can commercialize lab discoveries. Long-term success of CO_2 reuse in food systems depends on public perception

Conclusions and Strategic Recommendations

Conclusion

In the context of the Gulf Cooperation Council (GCC), this analysis has shown that one of the most established, feasible, and strategically important paths in the larger carbon capture and utilization (CCU) landscape is the reuse of carbon dioxide (CO_2) in the food business. The food industry already incorporates CO_2 as a functional input across several stages of the value chain, including preservation, packaging, refrigeration, fermentation, and product stabilization, in contrast to many other industrial sectors where its use is still technologically uncertain or economically limited. This intrinsic compatibility also protects and occasionally reinforces food quality and system efficiency, which allow for rapid emission reductions. Structural challenges such as extreme climate stress, energy-intensive cold chains, absence of fertile arable land, intense dependency upon food imports, and high food-security priorities have also made CO_2 reuse a strategic priority in the GCC.

These characteristics of the regions elevate CO_2 at this level from a peripheral sustainability issue to a systemic asset that can help enhance supply chain resilience whilst also contributing to future food security, cutting food waste, and preserving food. CO_2 reuse pathways also vary widely along technical maturity levels, from commercial physical applications to advances in biological and synthesis methods that re-shape the nature of food production and the extent to which it can be scaled to the limits set by land and freshwater versus vice versa. These pathways point not in opposite directions, but to a similar direction, and an evolutionary and synergistic way forward, moving food systems toward gradual gains toward greater circularity and decarbonization.

It underlines a high reliance on the system for both tech and cost sustainability. Coupled capture, purification, and utilization technologies continually outperform separate methods–which is something especially important when it comes to industrial clusters or food processing plants. At the same time, food grade purity limits are the basic condition of separating food sector carbon capture and utilization (CCU) from utilization in energy or construction systems to guarantee public confidence, quality assurance, and regulatory clarity. Here we propose recycling CO_2 has to do not with an emission management plan.

Recommendations

This review provides recommendations that have a strong saliency for strategic guidance regarding industry actors, politicians and the scientific community of research. Emphasizes CO_2 recovery and reuse retrofitting in high-volume applications where CO_2 is abundant (e.g., cold-chain logistics, dairy processing, meat processing, food industry beverage manufacturing). In addition, companies should work together and match their Carbon Capture Utilization solution so that the collection and utilization of the same system is linked up in production facilities or the industrial compounds in coexistence, so there are lower costs of purification and better system performance. And gradual adoption is recommended through time, which is achieved by physical reuse of existing materials and then introducing it with decreased costs into biological conversion. GCC countries: a harmonized and transparent policy regime for regulating food grade CO_2 obtained from collected sources should be developed, which will allow GCC states to implement the system on a large scale. The entire solution would need to be tailored to maintain security measures, with emphasis on purity tests specific for each application's level, traceability and validation requirements always.

However, a lot of financial incentives need to be implemented, such as those which can be capital subsidies, low interest loans, or other operational support mechanisms to overcome this initial cost barrier. If CO_2 reuse criteria were integrated into nationwide greenhouse gas accounting standards and food sustainability systems, this could align climate policy with international reporting obligations and concerns about food security. Integration of process control, energy efficiency and scaling-up engineering — rather than just having scientists acting as separate reaction pathways but technology developers managing different parts — should take precedence. For proper accounting of regional energy systems, climatic considerations and infrastructure needs, specifically GCC-specific techno-economic reviews and life cycle assessments will be required. In addition, public–private demonstration projects should be formed to evaluate new carbon-to-food technologies, including microbial and algal systems in practical working environments. Such demonstration is needed for reducing technology ambiguity and influencing legislation that may enhance public confidence in new systems of food production.

Author Contribution Statement

Mohammed Saleh Al Ansari (Corresponding Author):

Conceptualization; Methodology; Supervision; Project administration; Writing – review & editing.

Zeba Khan:

Investigation; Data curation; Formal analysis; Writing – original draft preparation.

Hajabanu Shaikh Mohammed Essa:

Resources; Validation; Visualization; Writing – review & editing.

Mohd Arif:

Software; Data processing; Technical support; Visualization.

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