SUSTAINABILITY AND CARBON NEUTRALITY THROUGH BIO-BASED SOLUTIONS:
A Lifecycle, Safety, and Carbon-14 Perspective

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Abstract

Bio-based materials have become essential enablers of industrial decarbonization and circular economy progress. This paper examines the transformative potential of bio-based chemicals, highlighting the pioneering experience of India Glycols Ltd. (IGL), the world's first producer of ethylene oxide from renewable bio-ethanol. IGL's integrated biorefinery demonstrates that large-scale bio-based production can be technically competitive, environmentally superior, and inherently safer.

Sustainability verification through Life Cycle Assessment (LCA, ISO 14040/14044) and Carbon-14 (C-14, ASTM D6866) analysis confirms 40–60 % reductions in greenhouse gas emissions, 100 % renewable carbon content, and improved health and ecological outcomes. IGL's Safety-Health-Environment (SHE) management- certified to ISO 14001, ISO 45001 and aligned with Responsible Care ensures that decarbonization advances worker and community safety alike.

The discussion connects green chemistry, empirical sustainability assessment, and SHE excellence with broader policy and SDG commitments (3, 12, 13). IGL's model illustrates that carbon neutrality is achieved not only through innovation but through measurable, verifiable, and safety-centred action- rooted in nature, powered by science.

1. Introduction

The chemical industry underpins modern civilization yet remains responsible for substantial greenhouse-gas emissions and occupational hazards. Conventional petrochemical processes rely on finite fossil resources and expose workers and ecosystems to toxic intermediates. The global transition toward sustainable industry thus demands solutions that reduce carbon intensity while improving safety and health outcomes.

Bio-based chemicals, derived from renewable agricultural or biological feedstocks, close the carbon loop by cycling atmospheric CO_2 through plant photosynthesis. Unlike fossil routes that release ancient carbon, bio-based processes return recently captured CO_2 to the biosphere, a prerequisite for carbon neutrality. In addition, they often replace carcinogenic or persistent substances with safer, biodegradable alternatives.

India Glycols Ltd. has pioneered this transition since 1989 by commercializing bio-glycols, bio-ethylene oxide, bio-EO derivatives & specialty chemicals using sugarcane-molasses-derived ethanol. Its success proves that sustainability, profitability, and safety can co-exist at industrial scale. The company's ISO 14001 and ISO 45001 certified systems, HAZOP and LOPA-based risk controls, and Responsible Care commitments embody how environmental responsibility and process safety can advance together.

Two scientific tools, LCA and C-14 radiocarbon analysis, lend credibility to bio-based claims. LCAs quantify cradle-to-gate environmental burdens; C-14 testing verifies the biogenic carbon fraction. Together they ensure transparency and authenticity in green labelling and sustainability reporting.

This paper therefore aims to:

1. Present the sustainability and carbon-neutrality performance of bio-based solutions through IGL's case.
2. Show how SHE management underpins sustainable growth; and
3. Demonstrate the role of LCA and C-14 analysis in substantiating environmental and safety benefits.

2. Bio-based Materials: Sustainability and SHE Dimensions

2.1 The Bio-based Paradigm

Fossil-based chemistry is both resource-intensive and pollution-intensive. Bio-based chemistry replaces fossil carbon with renewable carbon captured in biomass, allowing climate and

safety co-benefits. Feedstocks such as molasses, starch, or lignocellulosic residues serve as renewable carbon pools that can be continually regenerated.

2.2 Sustainability Benefits

- **Climate & Energy:** LCAs show 40–70 % GHG reduction and major fossil-energy savings for bio-glycols and ethoxylates. Renewable power integration further enhances neutrality.
- **Resource Efficiency:** By converting molasses into chemicals, IGL exemplifies industrial symbiosis and circular resource use.
- **Environmental Performance:** Bio-routes show lower acidification, eutrophication, and ecotoxicity, with products readily biodegradable and less persistent in nature.

2.3 Safety & Health Advantages

- Reduced Worker Exposure: Bio-routes avoid benzene, toluene, formaldehyde and such other typical of petrochemical synthesis. Producing EO from ethanol eliminates naphtha cracking and its carcinogenic by-products.
- Community Health: Cleaner effluents, lower VOC emissions, and biodegradable outputs minimize environmental toxicity.

2.4 Global Momentum

Regulatory and market frameworks now reinforce bio-based adoption: Bio-Economy Mission, and certification systems like Bonsucro, ISCC, RSB, RSPO and others. Growing consumer focus on chemical safety under REACH and national standards strengthens this shift toward safer, renewable materials.

3. India Glycols Ltd.: Integrating Biorefinery and SHE Excellence

3.1 Company Overview

IGL operates the world's only commercial bio-ethylene glycols and bio-ethylene oxide plant. Its Kashipur integrated biorefinery transforms molasses into ethanol, bio-ethylene, bio-glycols, bio-EO, bio-EO derivatives and bio-specialty chemicals. The group also produces nutraceuticals through Ennature Biopharma, the Natural Ingredients Division at Dehradun. Green chemistry principles- atom economy, hazard minimization, and design for degradation- govern all operations.

3.2 Biorefinery Model and Benefits

Molasses fermentation yields ethanol, dehydrated to ethylene and oxidized to EO.

Benefits:

- Waste valorisation and circularity.
- Reduced fossil dependence and CO_2 emissions.
- Lower toxic by-products (no PAHs or benzene).
- Effluent from distillery utilization- spent wash concentration followed by incineration generates steam/power under zero liquid-discharge regimes.

3.3 SHE Framework

- **Management Systems:** ISO 14001 and ISO 45001 certified; continuous improvement culture.
- **Process Safety:** HAZOP, QRA, MOC, DCS automation, ESD systems, LOPA redundancy.
- **Occupational Health:** Medical surveillance, PPE compliance, and contractor training under a "Zero Harm" vision.
- **Environmental Protection:** Advanced effluent treatment, air-emission monitoring, waste recycling.
- **Community Safety:** Integrated emergency plans with district authorities and public safety awareness programmes.

3.4 Strategic Value of SHE

SHE excellence builds regulatory confidence, customer trust, employee engagement, and operational resilience- transforming compliance into competitive advantage.

4. Scientific Tools for Sustainability and SHE Verification

4.1 Need for Evidence

Amid "green claim" inflation, credible verification is essential. IGL employs two complementary methods- LCA (ISO 14040/44) and C-14 (ASTM D6866)- to prove both impact reduction and renewable origin.

4.2 Life Cycle Assessment (LCA)

- **Scope:** Cradle-to-gate analysis- system boundaries include- sugarcane cultivation, molasses production at the sugar plant, ethanol production at distillery, ethylene glycols & ethylene oxide production at MEG

plant of IGL, EO derivatives & specialty chemicals, utilities, and transport.

- **Findings:** 40–60 % lower GHG footprint; reduced primary energy demand; lower toxicity and water use.
- **SHE Relevance:** LCA identifies occupational and community risk hotspots e.g., pesticide exposure in farming or effluent toxicity- guiding continuous improvement and safer process design.

4.3 Carbon-14 Radiocarbon Analysis

- Principle: Living biomass contains C-14; fossil carbon does not. ASTM D6866 measures biogenic carbon fraction.
- Application: Independent labs confirm 100 % bio-carbon in IGL's glycols and EO- derivatives, supporting global ecolabels.
- SHE Relevance: C-14 verification assures consumers of genuine renewable origin and minimises "greenwashing," reinforcing regulatory and market trust.

4.4 Complementarity and Integration

C-14 defines *origin;* LCA quantifies *impact*.

Their integration informs:

- Product stewardship and SDS updates,
- Process optimization using energy and safety data,
- Supplier engagement on safe, low-impact practices, and
- Customer assurance of verified renewable content.

IGL aligns these tools with UN SDGs, BRSR, Responsible Care, and ISO 14067, positioning itself as a science-based sustainability leader.

5. Bio-based Solutions, Circular Economy, and Societal SHE Benefits

5.1 Systemic Impact

Bio-based manufacturing decouples growth from fossil dependency while advancing occupational and community health. The benefits extend from farm to consumer.

5.2 Circular Economy in Practice

- **Agricultural By-products:** Molasses utilization prevents waste and groundwater contamination.
- **Resource Loops:** Concentrated spent wash incineration supplies process steam and energy
- **Design for Degradation:** Products engineered for biodegradability reduce aquatic toxicity.
- **Industrial Symbiosis:** By-products like CO_2 and fusel oil are valorised in downstream applications.

5.3 SHE Benefits Across the Chain

- **Agriculture:** Training suppliers on safe agrochemical use lowers exposure.
- **Manufacturing:** Biorefineries operate under lower pressures than petrochemical crackers, reducing explosion risk.
- **Consumers:** Bio-based cosmetics and detergents offer safer, biodegradable formulations.
- **Communities:** GHG and effluent reductions improve air and water quality; public emergency drills build preparedness.

5.4 Alignment with SDGs

Bio-based transitions advance- SDG 3 (Health & Well-being), SDG 6 (Clean Water), SDG 12 (Responsible Production), and SDG 13 (Climate Action). The health and safety dividends of carbon reduction make these goals mutually reinforcing.

5.5 Trust & Market Growth

Verified SHE performance fosters trust among consumers, regulators, investors, and communities- creating a durable license to operate and a market edge in ESG-driven economies.

6. Policy, Collaboration, and Future Pathways

6.1 Policy Drivers

India's Ethanol Blending Program and Bio-Economy Mission, alongside global instruments for Green Preferential market, catalyse demand for renewable carbon. Harmonized global standards for C-14 validation and product carbon footprints remain priorities.

6.2 Collaboration as Catalyst

- Industry–Academia: Joint R&D work, and safety analytics.
- Industry–Government: Co-design of carbon-credit and green-procurement policies.

- Cross-Sector: Automotive, FMCG, and pharma firms collaboration on bio-alternatives.
- Community: Transparent risk communication and participatory safety drills.

Such cooperation ensures innovations serve both markets and society.

6.3 Future Directions

- Renewable Energy Integration: Green hydrogen and solar power to deepen decarbonization.
- Digital Safety Analytics: AI-driven monitoring for predictive accident prevention.
- Next-gen Feedstocks: Lignocellulose, algae, and non-food biomass to enhance sustainability. Transforming industrial emissions, carbon dioxide, and gasified waste into recycled carbon ethanol- a building block for a wide range of sustainable products.
- Standardized Metrics: Global adoption of ISO 14067 and ASTM D6866 with health & safety KPIs.

6.4 The Human Core of Carbon Neutrality

A process cannot be called “sustainable” if it compromises worker safety or public health. Carbon neutrality thus demands integrated SHE governance- linking environmental targets with occupational and community well-being.

7 Conclusion

The IGL case confirms that bio-based industrialization can achieve measurable decarbonization while elevating Safety, Health, and Environment performance. LCA quantifies benefits, C-14 validates origin, and robust SHE systems safeguard people and ecosystems.

True sustainability is therefore science-verified, safety-secured, and collaboration-driven, a pathway where renewable carbon cycles and human well-being advance together toward a safer, healthier, and carbon-neutral world.

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