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CIRCULAR CONSTRUCTION PROGRAMME

Building Tomorrow: Transforming the Construction Sector for Inclusive and Sustainable Growth

Acknowledgements

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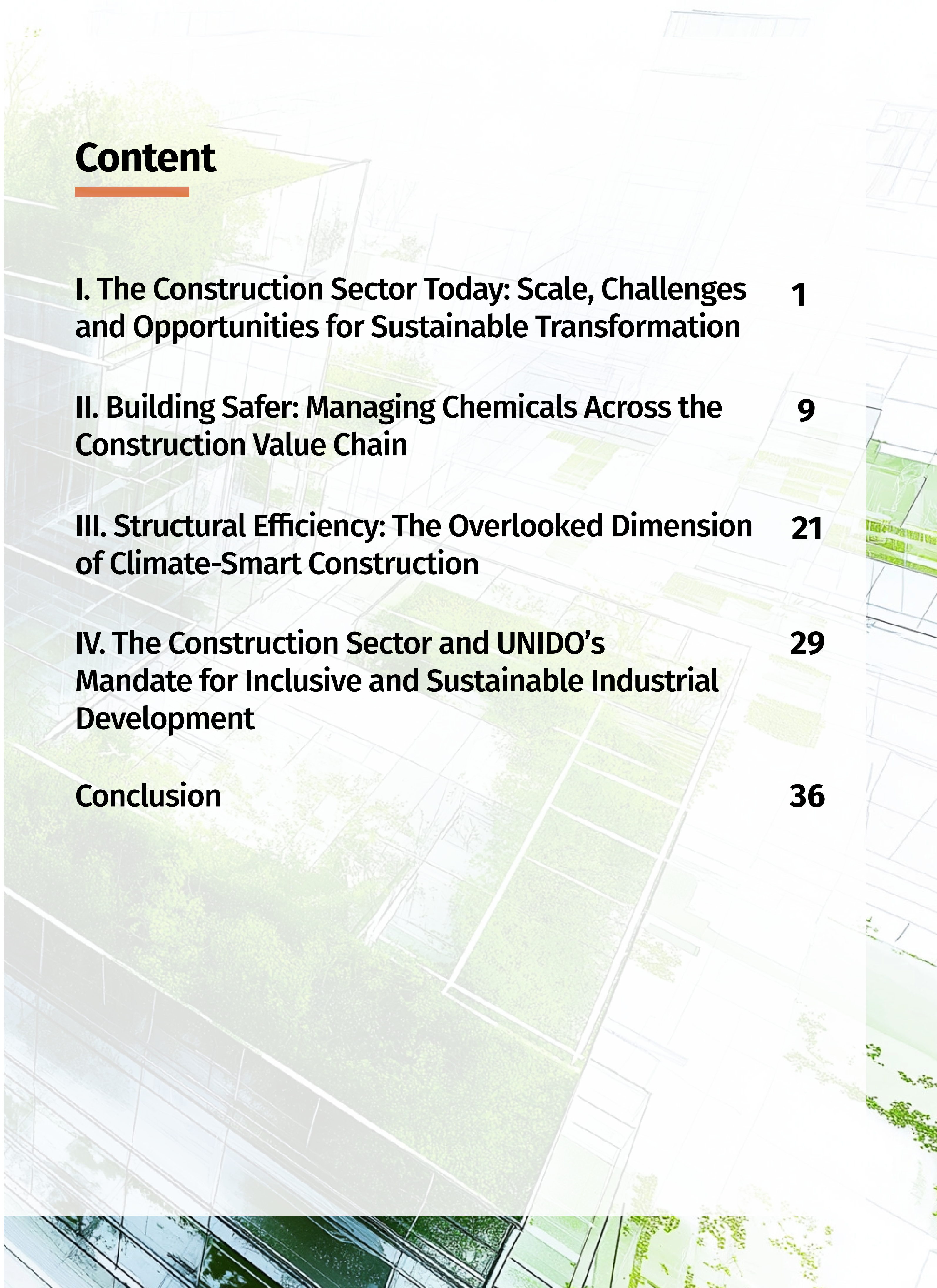

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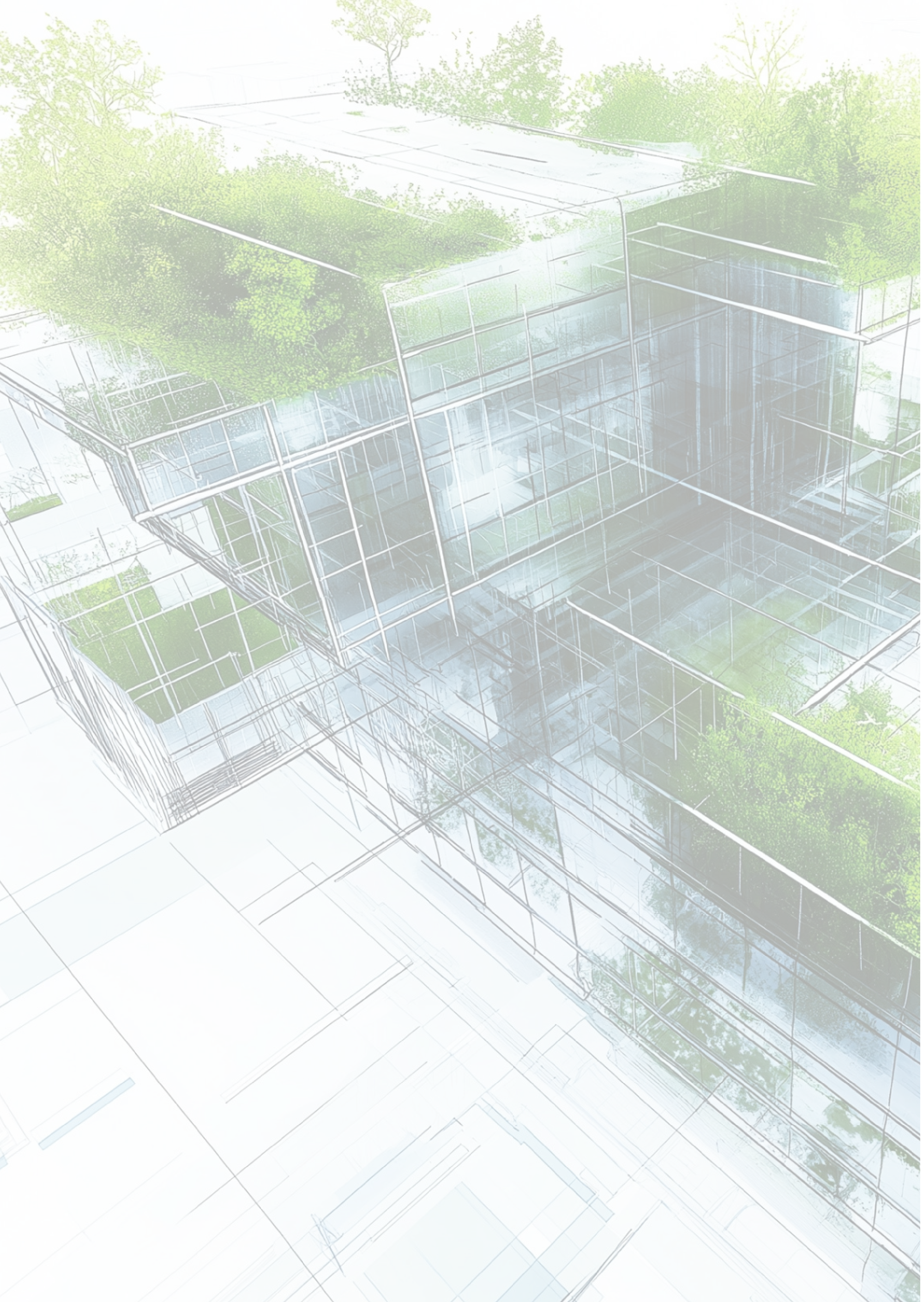


Foreword

Building Resilient Industrial Futures Through Circular Construction

The transition toward more circular and resilient economies is rapidly becoming a strategic priority for governments and industries worldwide. In a context marked by climate pressures, resource constraints, growing infrastructure demand, and evolving global supply chains, the construction sector stands at the center of a broader transformation reshaping industrial development. As one of the world's largest industrial ecosystems, construction influences not only the built environment, but also industrial productivity, material flows, investment patterns, employment, and long-term economic competitiveness.

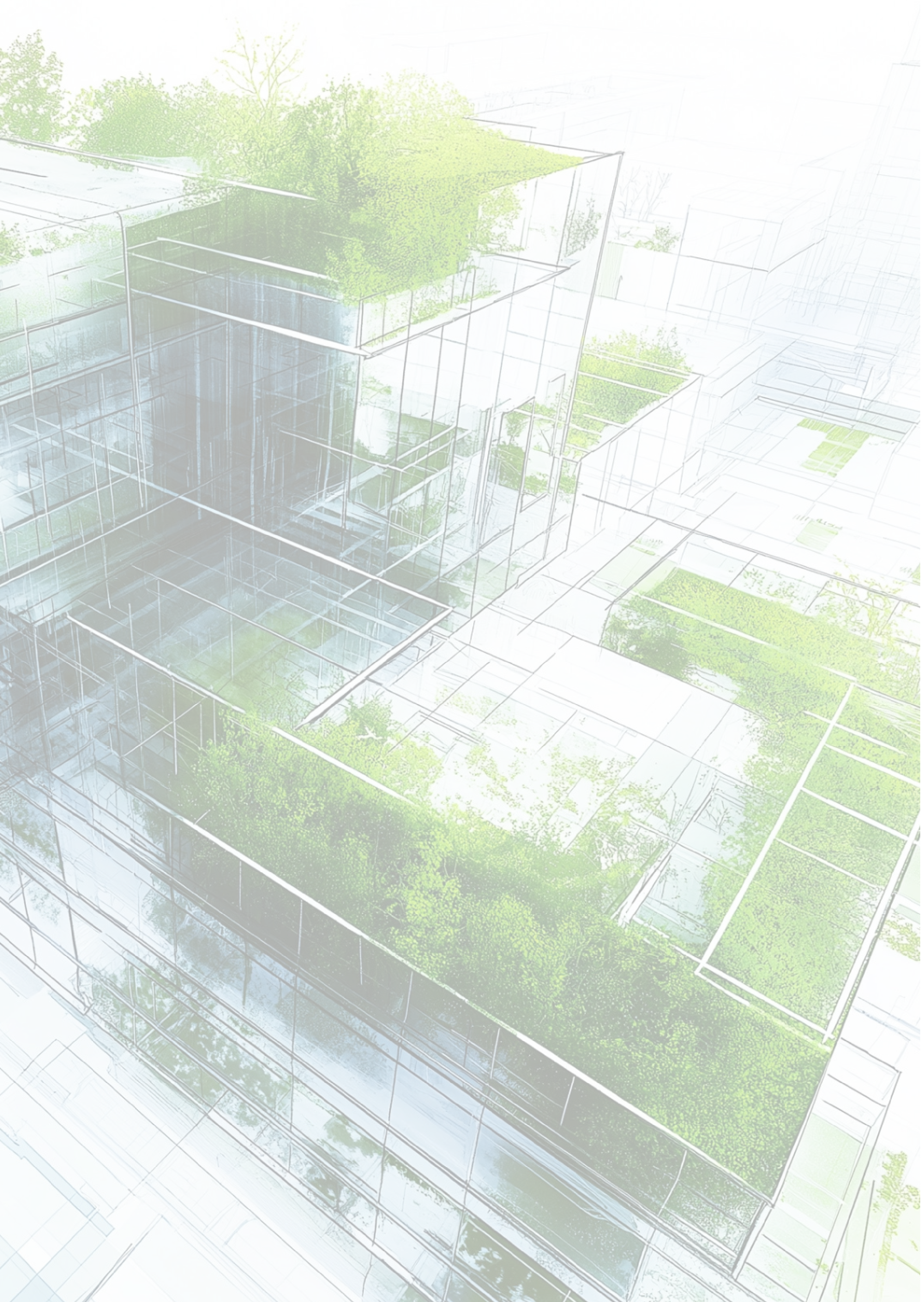
The scale of future infrastructure needs, particularly across developing and emerging economies, makes the sector a critical lever for advancing sustainable growth and industrial resilience. Increasingly, countries are recognizing that circular approaches are not merely environmental considerations, but strategic economic instruments capable of strengthening resource efficiency, reducing exposure to supply-chain volatility, supporting industrial innovation, and improving long-term development outcomes. In this evolving landscape, circular construction represents an important opportunity to align infrastructure expansion with industrial modernization and climate-resilient growth.

Through its mandate on Inclusive and Sustainable Industrial Development, the United Nations Industrial Development Organization supports its Member States in advancing integrated industrial solutions that connect policy, technology, investment, innovation, and international cooperation. Technical cooperation remains essential to help countries build institutional capacities, foster innovation ecosystems, facilitate partnerships, and translate global sustainability ambitions into practical and scalable implementation pathways.

As circular economy approaches gain momentum globally, the construction sector presents significant opportunities to strengthen industrial competitiveness while reducing environmental impacts and supporting long-term economic stability. Achieving this transformation will require stronger partnerships, integrated policies, technology cooperation, and coordinated international action capable of accelerating implementation at scale. The future of construction will not only depend on the infrastructure societies build, but on the resilience, efficiency, and sustainability embedded within the industrial systems that support it.

Ciyong Zou

Deputy to the Director General and Managing Director of the Directorate
of Technical Cooperation and Sustainable Industrial Development
United Nations Industrial Development Organization (UNIDO)



Foreword

The twenty-first century will be defined by how the world builds.

As countries face the combined pressures of rapid urbanization, climate change, resource scarcity, and rising infrastructure demand, the need to rethink the built environment has become increasingly urgent. For the construction sector - one of the world's largest consumers of materials and generators of waste and emissions - the transition toward a circular economy represents an environmental necessity and a strategic opportunity to transform value creation, strengthen industrial competitiveness, and improve resource resilience.

Addressing these interconnected challenges requires a fundamental new approach to the built environment - one that moves beyond the traditional linear path of “take, make, and dispose” toward systems designed for durability, efficiency, reuse, recovery, and circular innovation across the entire construction value chain.

Circular construction can become a powerful driver of sustainable industrial development. It can drive a new generation of industries, accelerating innovation in materials and manufacturing, creating new business and employment opportunities, reducing dependency on virgin resources, and supporting climate and environmental objectives while improving the long-term performance and resilience of infrastructure and cities.

Through its Circular Construction Programme, the United Nations Industrial Development Organization aims to support governments, industries, financial institutions, and technical partners in advancing practical pathways for circular economy implementation in the built environment. This includes strengthening industrial capacities, promoting resource-efficient and low-emission production systems, supporting enabling policies and standards, and facilitating investment and knowledge partnerships that can help scale circular solutions across regions and markets. This transition also presents a major opportunity for industrial modernization, including the development of low-emission materials, circular manufacturing systems, digital construction tools, and new markets for resource-efficient technologies.

It is clear that the choices made today will define the cities, industries, and infrastructure of tomorrow. Accelerating the transition toward more inclusive, low-emission, and resilient production and construction systems will require collective action, strategic investment, and strengthened international cooperation in support of both prosperity and planetary sustainability.

Smail Alhilali

Director, Circular Economy and Green Industry Division
Directorate of Technical Cooperation and Sustainable Industrial Development
United Nations Industrial Development Organization (UNIDO)

I. The Construction Sector Today: Scale, Challenges and Opportunities for Sustainable Transformation

1. Building the Foundations of Inclusive and Sustainable Growth

A cornerstone of global prosperity

Construction is one of the world's most consequential industrial ecosystems. It delivers the housing, transport, energy, and social infrastructure that enable inclusive and sustainable growth, while anchoring upstream value chains in cement, steel, glass, and chemicals. Embedded in the 2030 Agenda for Sustainable Development, the sector contributes to SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production): key priorities aligned with UNIDO's mandate for Inclusive and Sustainable Industrial Development (ISID).

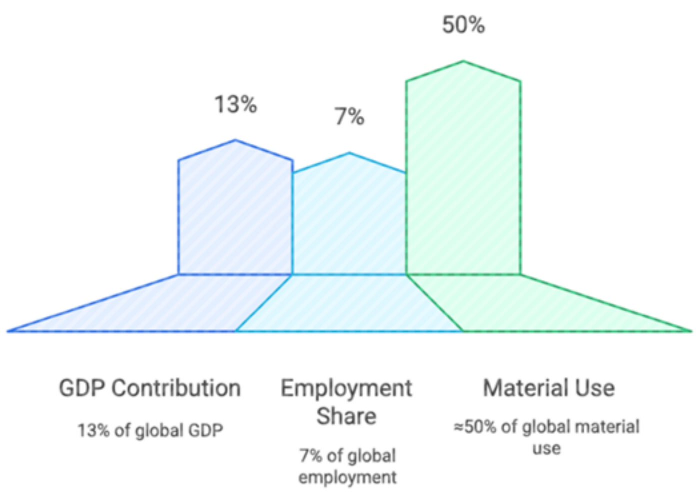
An economic engine of immense scale

In 2024, global construction output was estimated at approximately USD 11.4 trillion, with medium-term forecasts indicating growth to around USD 16.1 trillion by 2030 (See Ref. 1).

The International Labour Organization estimates that construction employs about 220 million people, or 7% of global employment (See Ref. 3). Each dollar invested in construction has strong multiplier effects across materials, manufacturing, design, logistics, and services, and is estimated to generate as much as USD 2-3 of broader economic activity across these sectors. This multiplier effect underscores the sector's critical role in advancing inclusive industrialization and enabling a circular, job-creating economy (See Ref. 4).

Together, these figures illustrate the construction sector's pivotal role in global prosperity - accounting for roughly 13% of world GDP, 7% of total employment, >USD 11 trillion in annual output, and linked to nearly half of global material extraction.

Global Construction Sector Impact



A century-defining urban transition

The twenty-first century will be defined by how the world builds. By 2050, 68% of humanity will live in cities, with over 90% of this growth occurring in Asia and Africa. Meeting future housing and infrastructure needs will require a major expansion of global building floor area. The Global Alliance for Buildings and Construction (GlobalABC) and the United Nations Environment Programme (UNEP) estimate that over the next 40 years, the world is expected to build around 230 billion m^2 of new construction, equivalent to adding a city the size of Paris every week (See Ref. 9; 60). Meeting sustainable infrastructure needs will require trillions of dollars annually through 2030; the Organisation for Economic Co-operation and Development (OECD), the World Bank and UNEP analysis estimates that around USD 6.9 trillion per year will be needed to align infrastructure investment with the SDGs and the Paris Agreement (See Ref. 9; 10; 11). Mobilizing this capital - through green bonds, public-private partnerships, and circular-construction incentives - is vital to align global construction with the Paris Agreement's 1.5°C pathway.

Regional growth patterns

1. Asia Pacific remains the epicentre of growth, contributing over 50% of projected market expansion to 2029 (See Ref. 1). While China's pace moderates, India, Indonesia, and Viet Nam are driving new waves of housing and industrial development. 2. Africa will experience the fastest urban expansion, doubling its urban population by 2050 and adding about 900 million people (See Ref. 13; 14). Priority investments include resilient infrastructure and affordable housing. 3. Latin America is upgrading aging energy and transport systems through public-private investment. 4. OECD countries are pivoting toward renovation and retrofit, guided by programmes such as the EU Renovation Wave, which targets 35 million buildings by 2030 (See Ref. 12).

Materials, energy and resource pressures

The OECD Global Material Resources Outlook to 2060 warns that construction-related material extraction - particularly sand, gravel, and limestone - could nearly double by 2060 if current practices persist (See Ref. 10). According to UNEP/GlobalABC's latest Global Status Report for Buildings and Construction 2025–2026, the buildings and construction sector accounted for around 37% of global carbon emissions, 28% of global energy consumption, and nearly 50% of global material extraction in 2024 (See Ref. 8). This illustrates the sector's systemic influence on climate and resource security. Without new approaches, rising demand for cement, steel, and glass could lock in emissions and ecosystem impacts for decades. Circular construction, resource efficiency, and the adoption of low-carbon materials offer viable pathways to decouple growth from resource depletion and emissions.

Construction Sector

200-220 million people

7% of global employment worldwide

By promoting safer, low-carbon, and resource-efficient materials, construction can become a driver of climate action, green jobs, and healthier communities. In this context, UNIDO supports its Member States in transforming construction into a low-carbon, circular, and regenerative industry, aligned with its mandate to advance sustainable industrial development.

37%
of global carbon emissions

28%
of global energy use

50%
of materials extracted

2.1 GtCO$_2$
released from cement, steel and aluminium used in buildings

A sector central to inclusive development

For developing economies, construction remains both a social stabilizer and an industrial accelerator. It stimulates local manufacturing, supports Small and Medium-sized Enterprises (SMEs), and creates accessible jobs for semi-skilled workers. The global construction sector is one of the world's largest employers; according to the International Labour Organization (ILO), it provides livelihoods to approximately 200-220 million people worldwide across a wide range of skill levels, from informal and semi-skilled labour to engineers, designers, and technical professionals (See Ref. 3).

Yet the industry faces structural weaknesses, including declining productivity, fragmented value chains, and limited capacity for innovation, resulting in higher occupational risks compared to other sectors, particularly in emerging markets. Without targeted interventions, these constraints could erode competitiveness and slow the transition to low-emission growth. Aligning industrial policy, financial mechanisms, skills development, and innovation can position the construction sector as a driver of inclusive, low-emission development, particularly in emerging and developing economies.

Innovation and industrial transformation

New technologies are redefining the sector's frontier. Building Information Modelling (BIM), digital twins, AI-enabled project management, and automation are boosting efficiency and transparency. Early adopters report 10–15% productivity gains and up to 70% waste reduction through modular and prefabricated construction. In many advanced construction markets, these tools are moving from pilot applications to mainstream practice, with large firms increasingly adopting BIM, digital project management and AI-enabled planning to improve efficiency, reduce waste and strengthen project oversight (See Ref. 24; 25).

Construction as a driver of local value creation

Construction stimulates jobs, local industry and innovation across the wider economy

Investment and policy imperatives

Meeting infrastructure and housing needs through 2030 will require USD 6.9 trillion annually (See Ref. 10; 11). The key question is not whether this capital will flow, but how it will be deployed. When directed towards sustainability, resilience, and innovation, these investments can transform construction into a catalyst for resource-efficient and inclusive industrial growth. If misaligned, they risk locking in carbon-intensive and low-productivity pathways for decades.

As the world builds at unprecedented speed, the true measure of progress will lie not in how much is built, but in how sustainably it endures, each structure embodying materials, energy, and human effort that will shape societies for generations. As construction continues to expand, its environmental and social footprint grows accordingly. The following section explores how the sector's material, chemical, and labour dimensions intersect with sustainability, and how innovation and policy can turn these pressures into opportunities for transformation.

The infrastructure built today will shape emissions, resilience and resource demand for decades.

2. The Sustainability and Social Footprint of Construction

A sector under increasing scrutiny

Construction is not only a driver of prosperity; it is also one of the most visible interfaces between industry, people and the environment. The choices made in buildings and infrastructure - from materials and chemicals to design, labour practices and end-of-life management - shape emissions, health, safety, resource use and resilience for decades.

This footprint is multidimensional. It includes energy use and embodied carbon, high demand for raw materials, construction and demolition waste, chemical exposure risks, worker safety challenges and pressure on urban resilience. Understanding these interlinked impacts is the first step toward transforming construction from a resource-intensive sector into a driver of safer, circular and inclusive industrial development.

UNIDO creates the conditions for effective waste management, and circular business models, while protecting health and responding to the national obligations under Multilateral Environmental Agreements.

2.1 Energy, Emissions, and Material Intensity

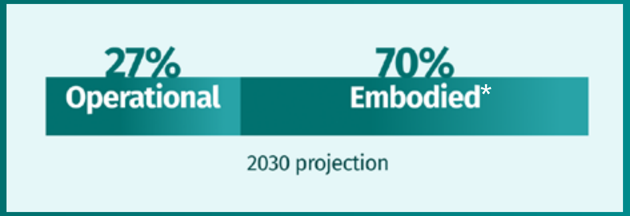
Energy use and carbon emissions stand out as the defining sustainability challenges.

1. In 2024, cement, steel and aluminium used in buildings generated approximately 2.1 GtCO$_2$, equivalent to around 9% of global emissions (See Ref. 8).

2. Aluminium and glass production contribute further indirect emissions through electricity-intensive processing.

Material inefficiency amplifies these impacts: construction typically loses 10-15% of materials as on-site waste, and end-of-life recovery rates rarely exceed 50% in most regions (Aggregated from UNEP 2023 and industry case studies).

As cities expand, embodied emissions from the production and transport of construction materials are expected to account for an increasing share of the sector's climate impact.



2030 projection

For highly energy-efficient new buildings, embodied emissions are expected to account for an increasing share of total lifecycle emissions, in some cases approaching 50-70% unless low-carbon materials, material efficiency and circular design strategies are adopted (See Ref. 9).

*Embodied emissions can represent an increasing share of lifecycle emissions in highly efficient new buildings.

2.2. Chemicals of Concern and Human Exposure

The construction industry is one of the largest downstream users of industrial chemicals, many hazardous if mismanaged. The Stockholm Convention targets persistent organic pollutants such as hexabromocyclododecane (HBCD), polybrominated diphenyl ethers (PBDEs), and short-chain chlorinated paraffins (SCCPs), commonly found in insulation and plastics.

The Minamata Convention addresses mercury emissions associated with cement production. In parallel, the Chemicals-in-Products (CiP) Programme, originally developed under SAICM and now aligned with the Global Framework on Chemicals (GFC), promotes chemical transparency, safer substitution, and improved traceability across product life cycles.

Improper demolition or disposal releases these substances into soil and water, undermining reuse and worker safety.

The use of specialized construction materials containing hazardous chemical additives can complicate, or, in some cases, effectively prevent the safe reuse and recycling of building materials. Early-stage interventions, such as chemical screening, safer procurement, and product labelling, are critical enablers of circular construction.

2.3 Social, Health and Labour Dimensions

Construction provides livelihoods for millions, yet remains one of the world's most hazardous and informalized industries.

1. The ILO estimates the sector accounts for ~ 20% of all occupational fatalities and ~ 60,000 work-related deaths annually (See Ref. 22; 23).

2. Many workers lack formal contracts, insurance, or protective equipment.

3. In low-income countries, child and migrant labour remain prevalent in artisanal brick-making and quarrying.

4. Poor building design and inadequate ventilation contribute to indoor air pollution, which the World Health Organization (WHO) links to millions of respiratory illnesses annually.

5. Gender inclusion in the sector remains limited, with women representing less than 15% of the global construction workforce.

Integrating gender-responsive training, robust safety standards, and social protection is essential to achieving just and sustainable industrial growth.

2.4 Waste, Circularity and Resource Efficiency

Construction and demolition waste (C&DW) is the largest solid-waste stream worldwide, estimated at 2.5-3 billion tonnes per year (See Ref. 20; 21). While metals are widely recycled, non-metallic fractions, such as concrete, bricks, plasterboard, glass, insulation, are often landfilled due to contamination, poor sorting, or uncertain reuse value.
Emerging best practices include:

1. Design for disassembly and modularity to enable material recovery.
2. Selective demolition and sorting to avoid contamination.
3. Recycled aggregates and low-clinker cements (LC^3, calcined clays).
4. Extended Producer Responsibility (EPR) policies for construction products.
5. Material passport systems to enable traceability and informed decision-making on reuse, recycling, or disposal pathways.

Circular approaches can cut embodied carbon by ~ 40% and reduce landfill waste by ~ 70%, while creating new industrial value chains in recycling and materials innovation. These estimates are drawn from UNEP 2023 and the Circularity Gap Report 2024, which model potential savings for construction materials through higher recycling rates and secondary-material use (See Ref. 9; 10).

Construction and demolition waste is the largest solid-waste stream worldwide, estimated at 2.5 - 3 billion tonnes per year.

2.5 Systemic Risks and Resilience

Beyond emissions and waste, construction faces rising systemic risks:

1. Climate hazards, including flooding, heat, and storms damage urban infrastructure.
2. Resource volatility, including energy and raw-material price fluctuations impact affordability.
3. Skills shortages, including digital and green construction competencies remain scarce.
4. Finance inequity, including SMEs and low-income housing markets lack access to green finance.

These pressures require integrated policy responses that combine climate resilience, skills development, occupational safety, financial inclusion, and industrial modernization.

2.6 Opportunities for Transformation

Despite its complex footprint, construction offers extraordinary leverage for sustainability if systematically transformed:

1. Safer chemistry: Replacing hazardous substances, including certain PFAS and brominated flame retardants, with safer alternatives can reduce occupational and environmental exposure, improve material circularity, and support compliance with international chemicals-management frameworks.
2. Circular design and efficiency: Applying design-for-reuse principles and material-efficiency strategies can significantly reduce waste, embodied emissions, and demand for virgin materials.
3. Green procurement: Public and private procurement policies can accelerate eco-innovation by creating demand for low-carbon, low-toxicity, and circular construction materials supported by standards and certification schemes.
4. Skills and formalization: Training, occupational safety, and stronger labour formalization can improve productivity, worker protection, and social inclusion across construction value chains.

The combined effect of these actions holds an immense potential. While existing building renovation generates 50-75% less emissions than new construction, circular design strategies could reach at least 10-50% decrease in greenhouse gas emissions compared to current practices, through circular design approaches and 'design for disassembly' (See Ref. 9).

The construction sector's expanding scale makes it both a source of risk and a force for renewal. By embedding climate resilience, resource efficiency, safe chemicals management and decent work into every project, construction can move from being the world's largest consumer of materials to its most visible champion of sustainability and inclusive growth.

3. A Sector at a Crossroads: From Impact to Transformation

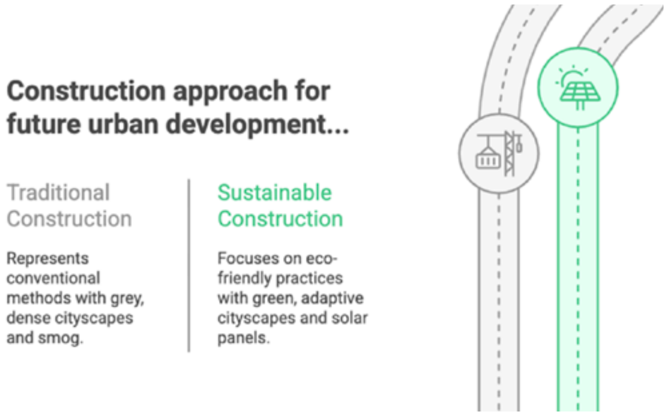
Building differently for a sustainable future

The construction sector stands at a pivotal moment. Its vast scale offers significant potential to advance climate action, resource efficiency, and inclusive growth, yet it also underpins some of the world's most material- and energy-intensive systems.

As noted in UNEP/GlobalABC's latest Global Status Report for Buildings and Construction 2025-2026, the sector remains a major source of emissions, energy consumption and material extraction, even as solutions for safer, lower-emission and more circular construction continue to mature (See Ref. 8).

The challenge ahead is not only to build more, but to build differently. Digital tools, circular design, and innovation in safer materials can help decouple growth from environmental harm while supporting resilient, low-emission livelihoods worldwide.

Yet while innovation has advanced rapidly, the sector's overall environmental and social footprint continues to expand. Bringing these forces into balance requires a transformation in how materials are designed, manufactured, and managed across their full life cycle.



Construction approach for future urban development...

Traditional Construction

Represents conventional methods with grey, dense cityscapes and smog.

Sustainable Construction

Focuses on eco-friendly practices with green, adaptive cityscapes and solar panels.

The converging pressures

The sector faces multiple, reinforcing challenges:

1. Climate: Recent research using a broader construction-sector footprint boundary estimates that construction-related materials and activities represent a substantially higher share of global CO_2 emissions (See Ref. 46).
2. Resources: Global material demand for construction could almost double by 2060 (See Ref. 10).
3. Labour: Construction remains one of the most hazardous industries, responsible for about 20% of workplace fatalities (See Ref. 22; 23).
4. Innovation: Productivity still lags roughly 30% behind manufacturing due to low digital adoption (See Ref. 24; 25).

Addressing these intertwined pressures requires transforming not just individual projects but the entire industrial ecosystem that supports them.

II. Building Safer: Managing Chemicals Across the Construction Value Chain

Strengthening institutional capacities and engaging diverse stakeholders can help ensure that construction policies are inclusive, context-sensitive and transformative.

Chemistry lies at the core of every structure humanity creates. It is what turns raw minerals into cement, sand into glass, and oil derivatives into polymers and coatings. Yet the same chemistry that makes our cities possible also determines whether they are safe to inhabit, efficient to maintain, and sustainable to rebuild.

Across the world, construction faces a central paradox: many of the substances that make buildings durable, safe and affordable can also undermine health, circularity and climate goals if they are not properly managed (See Ref. 26). Persistent organic pollutants, mercury, lead, and emerging contaminants such as PFAS have become part of the built environment itself, embedded in walls, foams, and paints that will remain in use for decades.

UNIDO's work positions chemical management not as a regulatory burden but as a foundation for inclusive, competitive, and sustainable industrial growth. By understanding where chemicals enter the construction life cycle - and how they can be substituted, tracked, and contained - countries can align industrial development with environmental protection and human wellbeing (See Ref. 26; 27; 45). The following sections map this hidden chemistry, its implications, and the opportunities to manage it more safely.

1. The Hidden Chemistry of How the World Builds

Every building material represents a chain of chemical reactions. From the calcination of limestone to produce cement, to the polymerization of plastics, to the cross-linking of resins that give coatings their sheen, chemistry is what holds the modern built environment together. These processes deliver durability, waterproofing, insulation, and aesthetics. But they also introduce substances that persist in the environment and human body long after their original function is fulfilled. With an estimated USD 11-12 trillion in annual output, even a small fraction of hazardous additives translates into vast global flows of pollutants.

Many of these substances fall within categories addressed under international frameworks or national regulations, including persistent organic pollutants such as PBDEs, HBCD and SCCPs in insulation foams and plastics; mercury emissions associated with cement production; PFAS* in selected coatings, sealants and waterproofing applications; VOCs and formaldehyde from paints, adhesives and composite wood products; and heavy metals such as lead and cadmium in pigments, stabilizers and legacy materials.

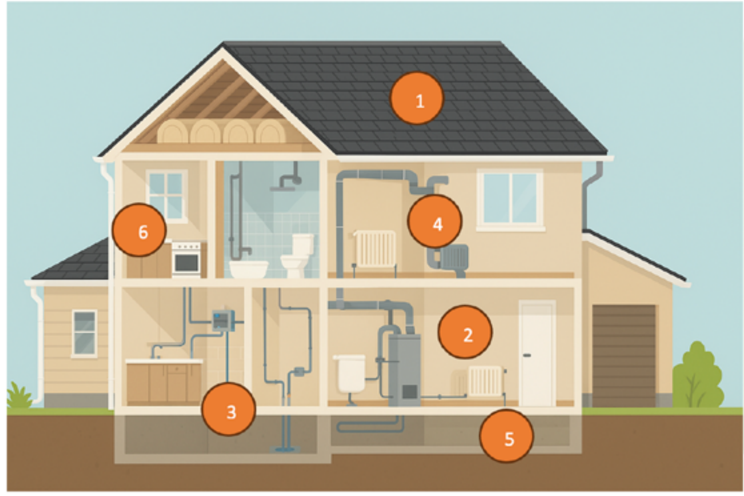
Their persistence is not accidental. Chemical formulations in construction aim for extreme stability, resisting fire, corrosion, and microbial decay.

The unintended result is that many of these compounds do not degrade once released, accumulating in air, soil, and water. Over decades, this creates a parallel infrastructure of invisible pollution: emissions from kilns and solvents during production, indoor exposure during use, and diffuse releases from demolition and waste.

For developing economies, where urban growth and industrialization are accelerating most rapidly, this hidden chemistry carries dual consequences. It supports jobs, innovation, and infrastructure delivery, but without preventive management, it also exacerbates health risks and constrains future circularity. Workers in small-scale cement, paint, and plastics enterprises often face the highest exposure levels, while informal recycling and demolition sectors become the final, unprotected link in the chain.

* PFAS are recognised as chemicals of concern due to their persistence, mobility, potential for bioaccumulation and long-term health and environmental risks.

UNIDO's approach reframes this challenge as an industrial opportunity: safer chemistry and cleaner production can reduce costs, enhance compliance with global standards, and open new markets for green construction materials. Managing chemicals responsibly therefore is not only a health or environmental imperative, it is also a competitiveness strategy for the industries that will build the next generation of cities.



1. Roof and Insulation (HBCD, TCPP, PFAS)
2. Walls, Paints and Coatings (VOCs, PFAS, Formaldehyde)
3. Flooring and Carpets (Phthalates, PFAS, Formaldehyde resins)
4. Piping and Plumbing (Lead, Phthalates, Chromium VI)
5. Concrete and Cement (Mercury, Chromium VI, SCCPs)
6. Windows, Doors and Sealants (Lead stabilisers, PCBs, PFAS Coatings)

Chemicals are embedded in every layer of the built environment - from the roof to the foundations - shaping not only how we build, but how safely we live (See Ref. 26; 30; 31; 32; 38; 39).

2. Chemicals Embedded in Construction Materials

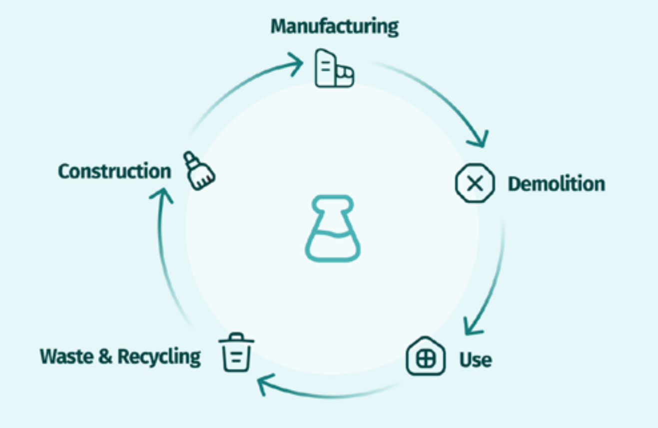
Buildings can be understood as chemical archives. Each wall, panel, pipe, coating or insulation layer contains substances designed to perform specific functions: accelerating curing, resisting moisture, preventing fire, increasing flexibility, or providing colour and finish (See Ref. 26; 40). What often remains invisible is the complex interplay between these substances and their long-term environmental and human impacts. From a life-cycle perspective, chemicals determine not only how materials perform at the time of construction, but how safely they can be occupied, maintained, and ultimately reused or recycled. At the manufacturing stage, chemical inputs define material strength and resistance; during use, they shape indoor air quality and human exposure, and at end-of-life, they decide whether components can re-enter the economy or must be treated as hazardous waste. The construction industry's dependence on chemistry is immense. The UNEP Global Chemicals Outlook II estimates that construction-related manufacturing accounts for more than a quarter of industrial chemical end-market demand, including cement, steel, glass, paints and plastics (See Ref. 2). Within these flows, hazardous substances are found in nearly every building element.

Invisible exposures across the life cycle

The risks associated with these substances are not confined to factories. They follow the material throughout its life cycle, manifesting in multiple exposure pathways:

1. During production, workers inhale dusts, vapours, and solvents - often without adequate protection. Small and medium enterprises, which dominate the building-materials sector in many developing regions, frequently lack access to safe handling training or emission controls (See Ref. 22; 23; 26).
2. During use, volatile compounds from paints, sealants, and composites accumulate indoors. Buildings with poor ventilation can trap these pollutants for years, leading to chronic exposure for occupants (See Ref. 38; 39).
3. During renovation or demolition, asbestos fibres, lead dust, and POP-contaminated particulates are released into the air. Informal demolition and recycling practices amplify these risks, especially in densely populated urban areas (See Ref. 26; 30; 31).
4. During disposal, open burning or uncontrolled dumping of construction waste releases heavy metals and persistent chemicals into soil and groundwater.

According to the World Health Organization (2023), poor indoor air quality, driven in part by emissions from construction materials, contributes to over three million premature deaths annually (See Ref. 38; 39). The International Labour Organization estimates that the construction industry accounts for around 20% of all occupational fatalities worldwide, underscoring the importance of stronger occupational safety systems, including controls for dust, chemical and particulate exposure (See Ref. 22; 23).



Chemicals travel through the full life of a building — from factory floor to demolition site — affecting air, water, and workers along the way.

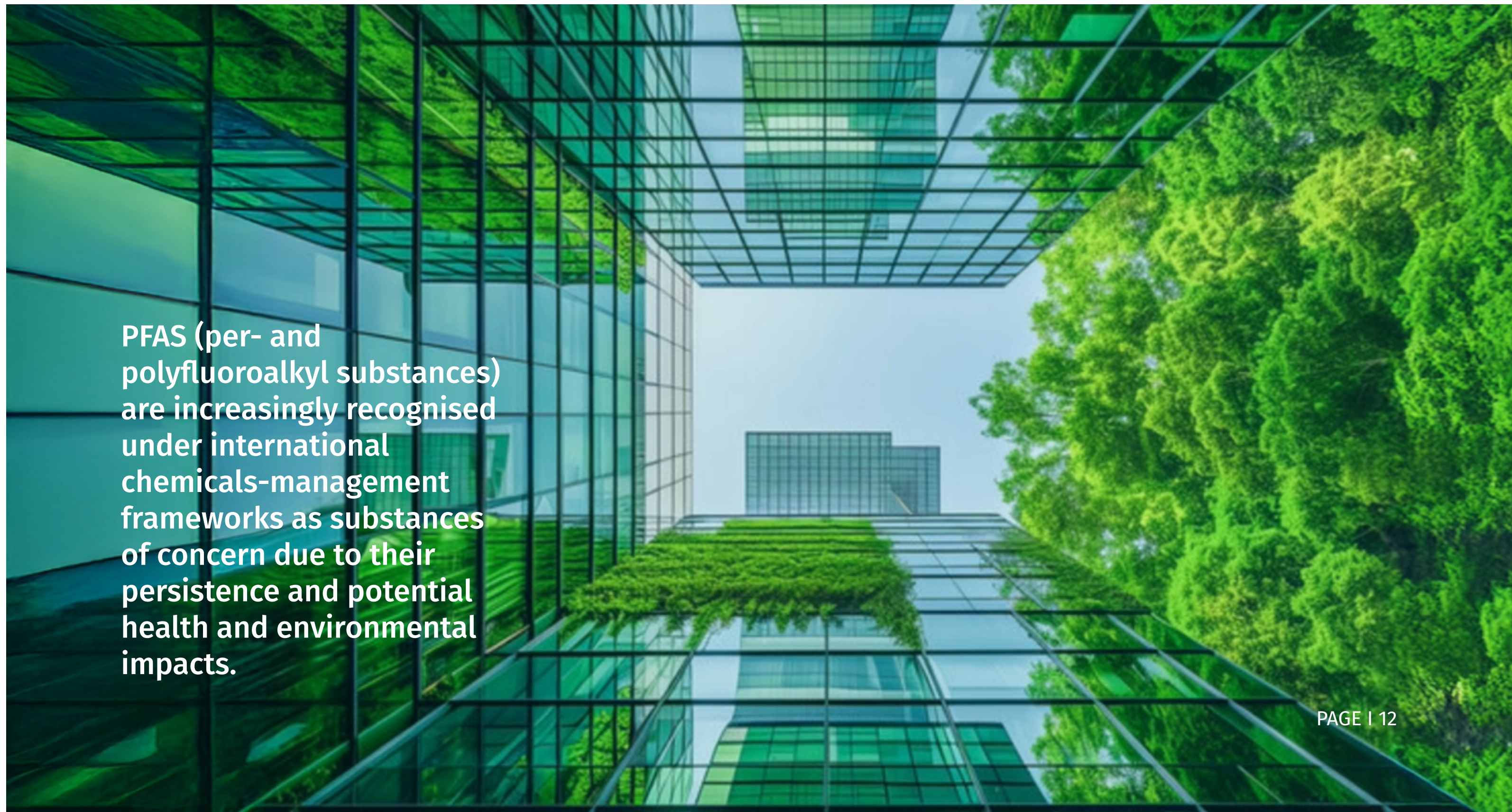
Material / Product	Key Chemical Groups	Function in Construction	Associated Risk
Insulation foams	HBCD, TCPP, PBDE flame retardants	Fire safety, thermal insulation	Persistent organic pollutants (POPs); bio-accumulative toxicity
PVC flooring, pipes, cables	Phthalates, lead and cadmium stabilizers	Flexibility, durability	Endocrine disruption; neurotoxicity
Paints, coatings, adhesives	VOCs, formaldehyde, PFAS in selected coatings, sealants	Surface protection, binding, waterproofing	Indoor air pollution; respiratory and skin irritation
Cement and concrete admixtures	Chromium VI, mercury emissions/residues, SCCPs in selected additives or sealants	Setting control, waterproofing	Dermal and respiratory irritation; toxicity to aquatic life
Metals and pigments	Lead chromate, cadmium sulfide	Colour and corrosion resistance	Carcinogenicity; environmental persistence
Legacy materials	Asbestos, lead paints	Historical applications	Chronic respiratory and developmental effects

Why these substances persist

Despite their known risks, many hazardous additives remain in widespread use because they deliver specific performance and cost advantages. Fire-retardant foams enhance safety; lead-based stabilizers can extend product lifespans in hot climates; chromium compounds improve durability and material performance. Replacing them requires not only technological innovation but also policy alignment, supply-chain transparency, and market demand for safer alternatives (See Ref. 26; 27; 29).

UNIDO's experience shows that substitution efforts are most effective when integrated into industrial policy, rather than treated as isolated environmental initiatives. Incentives for cleaner production, combined with technical assistance and training, can help SMEs shift to safer formulations without losing competitiveness.

The benefits extend beyond environmental performance, including improved worker safety, reduced liability risks, enhanced export readiness, and greater access to international green building markets. While the long-term objective is the progressive elimination of hazardous substances, the sequence and pace of action must reflect national circumstances, balancing environmental ambition with affordability, availability of alternatives, and social priorities such as housing and job creation.



PFAS (per- and polyfluoroalkyl substances) are increasingly recognised under international chemicals-management frameworks as substances of concern due to their persistence and potential health and environmental impacts.

3. Restoring the Loop: Safer Chemistry for Circular Construction

Circular construction envisions a future in which buildings are not end points of material use, but temporary repositories of resources, designed to be disassembled, reused, or re-manufactured with minimal waste. Yet this vision depends on the chemistry embedded within every product. When materials contain persistent, toxic, or poorly documented substances, their circular potential is compromised: they cannot be safely recovered, recycled, or repurposed (See Ref. 26; 43; 44).

Chemistry as a bridge - or barrier - to circularity

In a truly circular system, materials circulate within safe boundaries, what the Ellen MacArthur Foundation calls “safe loops” (See Ref. 43). In construction, however, hazardous chemical additives, including certain flame retardants, stabilizers, waterproofing agents and coatings can disrupt these loops.
1. Plastics and foams that contain brominated flame retardants (PBDEs, HBCDD) or PFAS-based coatings often become non-recyclable because they contaminate recycling streams or release emissions when heated (See Ref. 26; 30; 31).
2. Cementitious materials and slags containing mercury or chromium VI lose eligibility for safe reuse in secondary construction applications, locking hazardous residues into future structures.
3. Paints and sealants containing high VOCs or lead pigments can complicate safe recovery and recycling processes, forcing large quantities of material to landfill or incineration (See Ref. 26; 32).

These issues are not isolated technical problems, they are systemic challenges that determine whether a country’s building stock becomes a resource or a liability. Globally, less than 50% of construction and demolition waste is recovered (UNEP Circularity Gap Report 2024), and chemical contamination remains an important factor for down-cycling or disposal.

Restoring the material loop requires action at the source, through design and formulation, not at the waste stage.
1. Substitution and green chemistry: Transitioning to non-halogenated flame retardants, bio-based binders, and low-toxicity pigments ensures recyclability from the outset.
2. Traceability and transparency: Digital Product Passports (DPPs) and BIM-linked chemical inventories allow recyclers to distinguish between safe and hazardous materials.
3. Policy alignment: Extended Producer Responsibility (EPR) schemes that include chemical content criteria can incentivize manufacturers to phase out restricted substances.
4. Market signaling: Green-public-procurement policies that require POP-free, mercury-free, and low-toxicity materials create predictable demand for safer products, reducing cost barriers for industry.

These measures not only protect the environment but also build competitive advantage. Markets for certified low-toxicity materials are expanding rapidly across the European Union (EU), Asia, and Latin America, opening export opportunities for early adopters.

International frameworks enabling safer loops

Global environmental conventions provide the architecture for this transformation. Together they form a coherent platform for aligning national construction practices with international sustainability goals:

Convention / Initiative	Relevance to Construction
Stockholm Convention	Stockholm Convention Phase-out of POPs such as HBCDD, PBDEs, and SCCPs used in insulation, sealants, and plastics
Minamata Convention	Mercury use and emissions in cement and non-ferrous metal production
CiP Programme, originally under SAICM and now aligned with GFC	Promotes chemical transparency and traceability in building products
Basel Convention (Control of hazardous waste movements and trade in selected hazardous chemicals)	Regulates trade, transboundary movement, and disposal of hazardous building materials

Together, these frameworks offer a roadmap for detoxifying value chains, ensuring that materials can circulate safely within and beyond national borders. (See Ref. 27; 28; 29; 30; 31; 32; 33; 34; 35; 36; 37).

A systems perspective

Circularity cannot be achieved by technology alone. It also requires stronger coordination among designers, manufacturers, and regulators.

1. Designers need access to verified data on material composition to support safer specifications and informed material choices (See Ref. 27; 29).

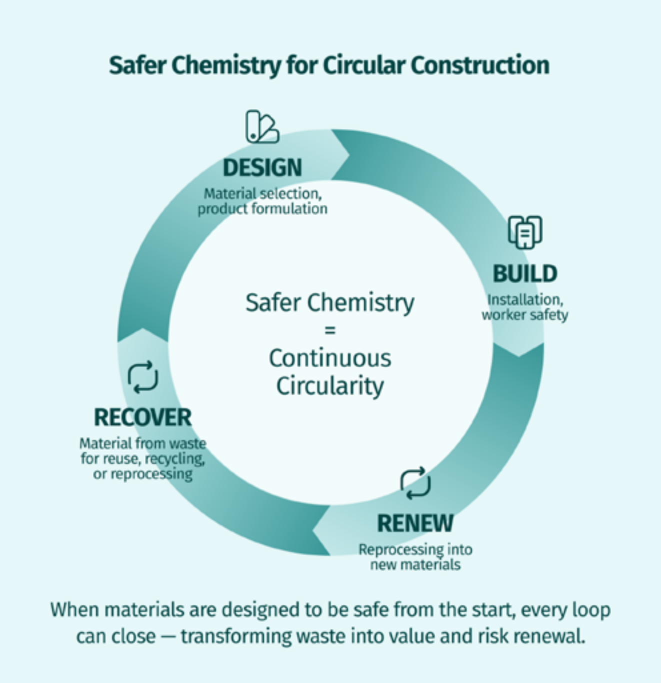
2. Manufacturers must integrate chemical stewardship into product development and quality control, enabling recovery of materials at end-of-life.

3. Governments play a central role in harmonizing standards, supporting substitution through fiscal incentives, and integrating chemical safety into green-building frameworks and procurement systems (See Ref. 26; 42; 45).

UNIDO’s ongoing projects illustrate how these roles intersect. In Morocco and Costa Rica, for example, pilot enterprises are supporting the transition away from POPs-containing foams toward safer alternatives, while contributing to national MEA obligations and strengthening opportunities within emerging green-procurement markets. This demonstrates how circular chemistry can function as a competitive enabler rather than a constraint.

The opportunity ahead

By improving transparency and reformulating materials at the source, countries can unlock significant environmental and economic benefits, including reduced hazardous-waste costs, healthier workplaces and improved access to sustainable finance.


Safer Chemistry for Circular Construction

When materials are designed to be safe from the start, every loop can close — transforming waste into value and risk renewal.

Circular construction built on safer chemistry can help transform the built environment into a long-term asset rather than a source of risk, sustaining prosperity without pollution.

In practice, achieving safe circularity is a gradual process. Some countries may initially prioritize safer waste handling and disposal, while others may invest directly in cleaner production, safe substitution or circular design approaches. The most effective entry points will depend on national priorities, institutional capacities, and the alignment of environmental, economic, and social objectives.

4. Managing Chemicals Before They Become Problems

Managing chemicals early in the value chain prevents harm, avoids costly remediation and enables circularity from the outset (See Ref. 26; 27). Across the construction ecosystem, proactive chemical management has proven not only an environmental imperative but also a strong business case: prevention can deliver higher economic value than later control, clean-up or remediation.

From reactive control to preventive design

Traditional approaches to chemical management have been reactive, responding to pollution or exposure incidents after they occur. This cycle of remediation traps governments and companies into recurring costs, reputational risks, and regulatory penalties. Preventive design, by contrast, addresses hazards at the source.

A growing number of countries now embed chemical-safety criteria into building codes, procurement frameworks, and industrial-innovation policies. These preventive systems integrate three essential principles:

1. Substitute early, substitute smartly

Replace hazardous substances with safer alternatives, including selected bio-based options before large-scale adoption locks in risk (See Ref. 26; 31). For example, calcium-zinc stabilizers now replace lead in PVC pipes; polymeric flame retardants are displacing brominated ones such as HBCDD; and water-based paints can substantially reduce VOC emissions, in some cases by up to 90% compared with conventional solvent-based alternatives (See Ref. 48).

2. Make safety transparent

Information is the backbone of prevention. Eco-labels, chemical inventories, and Digital Product Passports enable architects, contractors, and recyclers to know what substances are present, preventing the accidental re-use of toxic materials in future projects (See Ref. 27; 29).

3. Design for the full life cycle

Preventive design integrates health, durability, and recyclability into the same design approach. Materials chosen for low toxicity and easier disassembly extend the useful life of buildings while reducing exposure risk at demolition and re-use stages (See Ref. 26; 43; 44).

Managing chemicals early delivers the greatest returns

The most sustainable construction material is not one that is endlessly recycled - it is one that is safe by design.

Tools for prevention in practice

Prevention is implemented not by a single policy, but by a suite of instruments working together. Each of these instruments strengthens another. Digital tracking enhances transparency; transparency empowers procurement; procurement accelerates substitution. The outcome is a virtuous cycle where innovation and safety reinforce each other rather than compete.

Tool	Purpose	Example Applications
Green chemistry and safer-substitution programmes	Support R&D for non-toxic additives and binders	National cleaner-production centres promoting POP-free polymers
Green public procurement (GPP)	Use government purchasing power to shape markets	Low-VOC, mercury-free, or POP-free material criteria in public-housing contracts
Codes, labelling, and certification	Signal market preference for safer products	EU Ecolabel, BREEAM, and LEED health-based material indicators
Digital tracking (BIM, DPP)	Map and monitor chemicals within building assets	BIM-integrated chemical inventories for renovation planning
Skills and capacity building	Train workers and SMEs in hazard recognition and safe handling	Occupational-safety curricula and on-site awareness programmes

(See Ref. 22; 23; 26; 27; 29; 31; 45).

Protecting workers and livelihoods

Chemical safety is also a matter of social justice. Construction workers, especially in small enterprises and informal sectors, are among the most exposed populations. According to the ILO (2023), about 20% of all occupational fatalities occur in construction, and a significant share relates to chemical or particulate exposure.

Beyond reducing hazardous substances in materials, integrating occupational-health protocols into training and certification can improve worker protection and strengthen safety culture. Key measures include:

1. Mandatory use of personal protective equipment (PPE) combined with worker training on the safe handling of solvents or coatings;

2. Proper ventilation in paint shops, mixing units, and cement-grinding areas;

3. Routine air-quality and exposure monitoring on large worksites;

4. Inclusion of gender-sensitive safety guidelines, recognizing that women workers often face distinct exposure risks in finishing and cleaning roles.

Such measures elevate safety from compliance to culture, an essential pillar of inclusive industrial development.

In many developing economies, complete substitution or preventive design at the earliest stages may not always be realistic. Limited access to green chemistry inputs, higher costs, or the need for affordable housing may necessitate phased approaches. In such contexts, effective management can still occur downstream, through improved waste handling, safer recycling, or gradual technology transfer. UNIDO’s approach supports countries in identifying the most relevant combination of interventions along the value chain, ensuring that progress is both feasible and inclusive.

Cleaner production and industrial co-benefits

Cleaner-production approaches translate preventive design into factory practice. The advantages extend well beyond compliance:
1. Efficiency gains: Plants that substitute or minimize hazardous inputs can improve process control, reduce emissions and strengthen operational performance. In cement production, mercury-control measures and BAT/BEP (best available technologies and practices) approaches can be integrated with process optimisation, waste-heat management and improved environmental controls (See Ref. 32; 33).
2. Cost and risk reduction: Transitioning from solvent-based to water-based paints and coatings can reduce VOC emissions and associated exposure risks, while reducing the need for solvent handling and related waste-management controls (See Ref. 38; 48).
3. Market differentiation: Suppliers of POP-free foams and low-VOC coatings may gain improved access to green-building markets and international buyers with stringent environmental, social and governance (ESG) requirements.

In short, cleaner chemistry strengthens competitiveness while fulfilling global environmental commitments.

Policy integration for scale

For preventive chemical management to reach national scale, it must be embedded in policy frameworks and supported by appropriate financing mechanisms. Governments can:
1. Integrate chemical-safety objectives into national construction and industrial development strategies;
2. Link green-chemistry R&D with industrial-innovation incentives and fiscal measures;
3. Expand environmental-finance instruments, such as green bonds and environmental grants, to support safer-material transitions;
4. Encourage public–private collaboration through demonstration projects, partnerships and data-sharing platforms.

When prevention becomes part of national planning, the benefits multiply, cleaner air and water, lower healthcare costs, and a future-ready industrial base.

5. From Risk to Opportunity: Learning from Practice

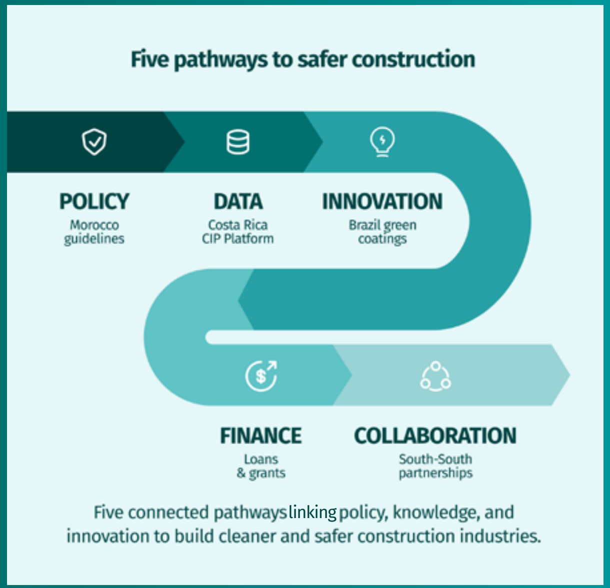
Chemical safety is often perceived as a regulatory burden. Yet UNIDO's experience shows it can become a driver of innovation, competitiveness, and resilience. When industries transition to safer materials and transparent supply chains, they not only reduce pollution but also unlock new markets and create decent jobs. In this way, sound chemical management strengthens every pillar of Inclusive and Sustainable Industrial Development: economic value, social inclusion, and environmental integrity.

Scaling transformation: five pathways to safer construction

Building on global experiences and established good practice, UNIDO identifies five interconnected pathways that can accelerate transformation across the global construction ecosystem. These pathways form the building blocks of a preventive, transparent, and innovation-driven chemicals economy (See Ref. 26; 27; 28; 29; 41; 42; 45).

1. Policy integration - Align construction and chemical policies.
Embed chemical safety objectives within national industrial, housing, and infrastructure strategies. Governments that integrate chemical management into building codes, procurement strategies and trade regulations can create predictable market conditions that reward cleaner production.
2. Transparency and data - Make information flow across the value chain.
Expand the use of Digital Product Passports, chemical inventories, and open databases. Transparency allows architects, recyclers, and investors to assess risk and choose verified low-toxicity materials.
3. Innovation ecosystems and capacity building - Connect R&D with enterprise action. Link universities, start-ups, SMEs, and technical institutions through green-chemistry incubators, technology-transfer platforms, and targeted training programmes. Strengthening technical and institutional capacities can accelerate local innovation, support safer substitution, and reduce dependence on imported hazardous substances.
4. Finance for transition - Reward prevention, not pollution.
Mobilize green bonds, environmental grants, concessional loans, and blended-finance mechanisms to de-risk investments in cleaner materials and technologies. Financial institutions are increasingly prioritizing circular and low-emission products within ESG portfolios.
5. Collaboration and partnerships - Build coalitions for impact.
Foster South–South and regional cooperation to share knowledge, harmonize standards, and scale technology transfer. Partnerships among governments, industry associations, and international organizations amplify the pace of change. Together, these pathways redefine chemical safety as a foundation for industrial modernization, turning risk into resilience and regulation into opportunity.

Five pathways to safer construction



Five connected pathways linking policy, knowledge, and innovation to build cleaner and safer construction industries.

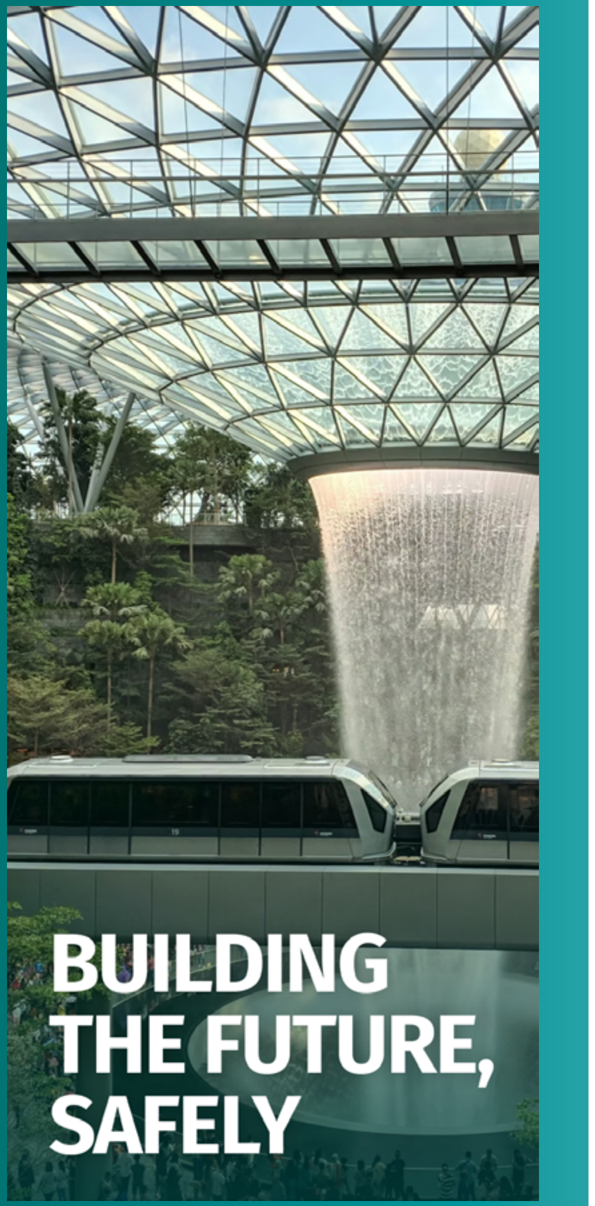
The multiplier effect

Each pathway reinforces another. Transparent data informs smarter policies; innovation attracts finance; partnerships scale success. The result is a self-sustaining transformation where economic growth and chemical safety advance in tandem.
UNIDO's experience shows that once industries adopt safer chemistry approaches, the benefits extend beyond compliance, including lower operational and compliance costs, improved worker safety and health, and increased export readiness for growing international green-construction markets.
As countries modernize their infrastructure, these integrated approaches prove that sustainable construction is not a niche agenda - it is the new baseline for industrial competitiveness.

6. Building the Future, Safely

Chemicals are the invisible scaffolding of modern civilization. They determine how long our bridges last, how breathable our homes are, and how safely our cities evolve. But they also define how the next century will be built, whether through depletion and pollution, or through innovation and renewal.

UNIDO leads the way: The benchmark for progress is not quantity, but responsibility, through safer materials, cleaner processes, and informed decisions that advance sustainable industrial development.



Every construction decision, coating applied, cement mixture selected, polymer produced, carries a chemical legacy. Together, these choices shape the resilience of societies, the health of communities, and the sustainability of industries. Managing this legacy responsibly is therefore one of the defining industrial challenges of our time.

UNIDO's role: linking policy, innovation and people

For much of the 20th century, construction progress was measured in scale and speed, how high cities could rise, how quickly new homes could be built, and how much material could be produced. The 21st century adds a new dimension: safety, transparency, and regeneration.

Sustainable construction is no longer optional; it is becoming a strategic necessity. The global building stock is expected to double by 2050, and every tonne of material embedded today will shape future emissions, exposure risks, and recyclability for decades to come. The challenge facing policymakers and industries is therefore not whether to change, but how to build differently using materials and chemistry that support safer and more sustainable outcomes.

1. Under the Stockholm Convention, UNIDO assists manufacturers in phasing out persistent organic pollutants and adopting safer alternatives for flame retardants and coatings (See Ref. 30; 31).
2. Through projects supporting the implementation of the Minamata Convention, industries reduce mercury emissions in cement and non-ferrous metal industries while improving energy and resource efficiency (See Ref. 32; 33).
3. Through projects aligned with the Chemicals-in-Products Programme, UNIDO supports traceability systems that empower producers and recyclers to make informed, safer choices (See Ref. 27; 28; 29).
4. Across all initiatives, the focus remains on people - strengthening SMEs' capacities, safeguarding workers, and supporting healthier communities that build, inhabit, and work within the built environment.

These interventions show that when global frameworks are translated into national policy, enterprise initiatives, and social protection, sustainability becomes both achievable and economically rewarding.

A vision for the next decade

The next generation of construction industries will not only build cities - they will build trust. Trust between governments and citizens seeking healthier urban environments; between workers and employers committed to safety and dignity; and between industry and nature, as technology shifts toward low-toxicity, circular materials.

By embedding chemical safety into every stage of the construction value chain, countries can:
1. Protect health and environment by reducing occupational exposure and indoor pollution;
2. Accelerate circularity by keeping materials in use and out of landfills;
3. Enhance competitiveness by opening access to growing international green-construction markets; and
4. Create inclusive opportunities through safer jobs, skills development and local value addition.

This transformation is already underway, driven by stronger policy coherence, digital transparency, and cross-sector collaboration. The challenge ahead is to scale these efforts, aligning every beam, brick, and binder with a vision of prosperity that supports both economic development and environmental sustainability.

The measure of success

The future of construction will not be measured by the height of skylines, but by the health of communities living beneath them. Success will not be measured only in concrete poured, but in emissions avoided, hazardous substances removed, and lives improved. Building safely means building strategically, embedding circularity, resource efficiency and life-cycle thinking into every stage of the construction value chain. Every safer and more resource-efficient material choice today is a commitment to future generations, demonstrating that economic progress and environmental responsibility can advance together.

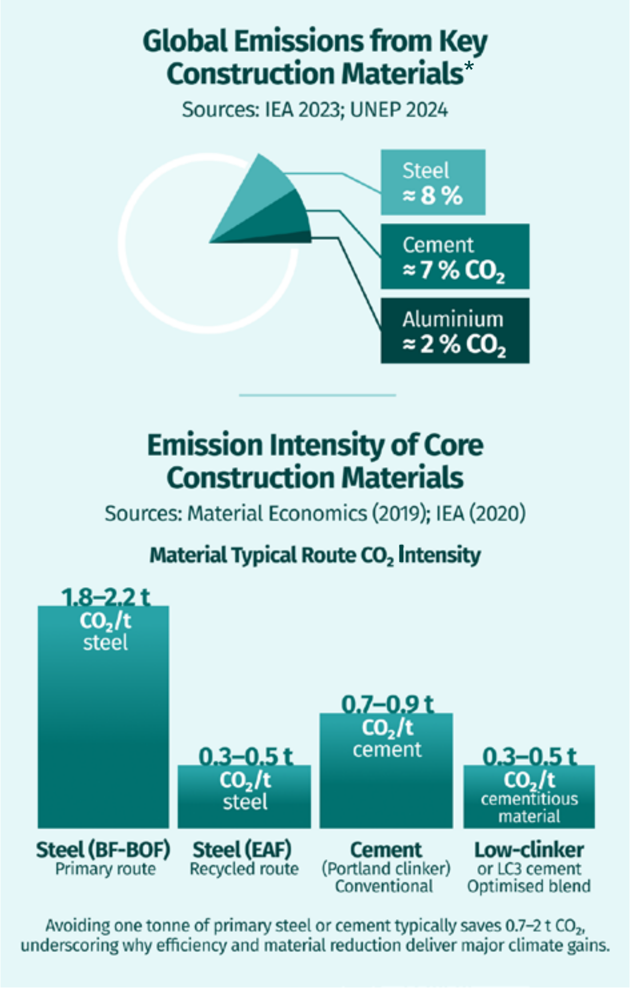
Ultimately, building safely is not about prescribing a one-size-fits-all approach, it is about enabling informed and context-specific decisions. Each country must balance environmental ambitions with social realities and economic constraints. Through policy guidance, technical assistance, and strategic partnerships, UNIDO helps countries define tailored pathways that strengthen health, resilience, and sustainable economic opportunity within their specific development contexts.

III. Structural efficiency: The Overlooked Dimension of Climate-Smart Construction

1. The Hidden Potential of Material and Structural Efficiency

A missing link in climate-smart construction

A substantial share of global greenhouse-gas emissions arises from the production of construction materials such as cement, steel, and aluminium. While operational energy efficiency in buildings has improved significantly, embodied emissions associated with material extraction, processing, manufacturing, and construction remain a major challenge.



As buildings become more energy efficient, the balance between operational and embodied impacts shifts dramatically. Historically, embodied energy, the energy consumed in producing and assembling building materials, represented only about 10-20% of total life-cycle energy demand (See Ref. 47). However, while improvements in system efficiency have sharply reduced energy use during the operational phase, the embodied energy has increased. As a result, the relative share of embodied energy and its associated greenhouse-gas emissions is increasing. In low-energy or passive buildings, materials and construction can already account for around 50% of total life-cycle energy demand (See Ref. 47). This trend underscores that as operational efficiency improves, managing embodied impacts becomes a decisive frontier for achieving genuinely climate-neutral construction.

Once built, every structure locks in material-related emissions for decades. In practice, many of a building's lifetime embodied-emission impacts are determined during the early design and procurement stages. Decisions related to grid layout, span length, and structural-system selection can significantly influence material consumption and embodied emissions. Studies and structural-efficiency pilot projects indicate that for typical steel- and concrete-framed buildings, optimizing these parameters can substantially reduce embodied CO_2 - in some cases by 40-60% - while also lowering structural-frame costs (See Ref. 49).

*Indicative global industrial-sector emissions associated with major construction materials. Figures represent total sector emissions, not emissions attributable exclusively to buildings.

Structural efficiency, or constructive efficiency, offers one of the most powerful yet under-utilized levers to reduce embodied emissions in construction. As a metric, it informs the use of materials more intelligently within load-bearing systems - minimizing waste and over-design, while maintaining structural integrity, functionality, and architectural expression.

Current pilot studies on real projects suggest that many building structures operate at relatively low levels of structural efficiency often in the range of approximately 1.5 to 4.5% - data on SE pilots can be accessed through tt-eu.com/SE, - equivalent to the old incandescent lightbulbs, with around 2.5% regarded as typical (See Ref. 49). These findings are broadly consistent with earlier research proposed under the 'Towards a Structural Efficiency Classification System', which highlighted the substantial gap between theoretical and practical material utilization in structural systems (See Ref. 55). This indicates that a large share of structural material capacity is underutilized. Closing even part of this efficiency gap could substantially cut global demand for steel and cement, offering one of the most effective and immediate pathways to reduce embodied emissions while maintaining safety and functionality.

This "hidden potential" is mirrored at the system scale. Material Economics finds that many construction projects use 30-50% more cement and steel than would be necessary with an end-to-end optimisation of design and material use (See Ref. 51). In the same analysis, a stretch scenario for the EU cement and concrete system, combining structural optimisation, lower cement content, and reuse of concrete elements, shows that cementitious material demand could fall by about 65% (≈ 121 Mt per year) by 2050, while maintaining the same built area and functionality. This illustrates the scale of improvement possible through structural and material efficiency alone, even before accounting for cleaner production routes.

2. Defining Structural Efficiency

Structural efficiency describes the relationship between the theoretical minimum amount of material required to achieve a given structural function and the actual quantity used in practice. Material and structural efficiency impact the entire life cycle of how we design, build, and use structures.

While material efficiency seeks to reduce the total quantity of energy-intensive materials needed to deliver a service (for example by reducing clinker content via supplementary cementitious materials), structural efficiency more specifically informs the i) layout, ii) technologies and iii) optimisation of building systems to use every unit of material to its fullest potential. In practice, its significance reflects on other metrics:
1. Self-weight multiplication coefficient: Current structures are so material-intensive that up to 2/3 of their capacity is to withstand its own weight, while theoretical optima would only need 1/100 (See Ref. 55).
2. Embodied carbon intensity: kg CO_2 embodied in the structure per m^2 floor area. 400 is nowadays assumed as a reasonable reference, while SE-informed designs can achieve well below 100 (See Ref. 55).

Efficient structures achieve closer alignment between form and force by:
1. Optimizing geometry through analysis, using existing tools for digital design, topology optimisation, and parametric modelling. This affects both the architectural and engineering layouts.
2. Leveraging material properties, such as compressive strength, tensile strength, ductility, or isotropy, informing material selection rather than compensating with excess mass; for example, concrete performs efficiently in compression, while steel is highly effective in tension; this can inform material selection in composite or hybrid systems.

Furthermore, structural efficiency is fully compatible with other sustainability measures, like:
1. Integrating reuse and adaptation, extending the life of existing assets; and
2. Designing for repair and disassembly, enabling future material recovery and reuse, rather than landfilling or downcycling, which reduces future demand for fresh emissions-intensive materials.

Together, these approaches form a continuum of complementary levers, each addressing a different stage of the material life cycle. They reinforce one another: less material used or reused means fewer emissions from extraction, processing, and transport, and a smaller scale of industrial transition required downstream.

Lever: Key Concepts & Techniques

1. Reduce need: Functional efficiency
Space optimisation; shared or multi-use buildings; right-sizing of floor area; avoidance of unnecessary new builds.
2. Use less: Structural optimisation
Grid and span optimisation; topology optimisation; high utilisation ratios; regular structural layouts; new systems informed by structural efficiency metrics.
3. Use better: Improved materials
Stiffer materials so they don't need to be oversized to meet serviceability criteria; low-clinker cements (e.g. LC^3); leverage the properties of different materials in composite or hybrid systems.
4. Use longer: Lifetime extension
Durable materials; design for maintenance, repair and adaptability; refurbishment and adaptive reuse instead of rebuilding.
5. Use again: Circularity and recycling
Design for deconstruction and reuse; traceability, high-quality recycling of steel, concrete and plastics; modular prefabrication of components.

These levers operate jointly: each reduces one term in the impact equation I = D × M × Y × E - demand, mass, yield, and emission intensity (See Ref. 47). Together they define the practical field of material and structural efficiency that underpins a net-zero industrial future.

A tangible illustration of how these levers reinforce one another is the combination of parametric modular construction and traceability. Standardized and digitally optimized components can be manufactured with high precision in controlled factory settings, reducing material use, overdesign, and construction waste. When modular systems are also designed for repairability, disassembly, and reuse, they can extend building lifespans, support future adaptation and reconfiguration, and enable the recovery and reuse of components in new structures. Traceability systems further strengthen these benefits by improving information flows on material composition, maintenance, and reuse potential throughout the building life cycle.

This makes parametric modular construction a strong example of how industrialized, digitally enabled building methods can strengthen the combined impact of material and structural efficiency across the entire value chain.

Assessment by organizations such as the UNEP, the IEA, and GlobalABC suggest that global implementation of industrialized, modular, and resource-efficient construction approaches based on such principles could reduce material consumption by 20-40%* (See Ref. 54; 55; 57; 59) and lower construction costs by 10-20%** (See Ref. 49), even after higher design-effort costs are considered.

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*20-40% material consumption figure spans findings on different materials (steel, cement, concrete, rebar), different efficiency strategies (structural optimisation, light-weighting, over-specification reduction, demand-side modelling), and different timelines and geographies.
**Good early stage design decisions can halve embodied CO_2 and lower structural frames' cost, which finds that the typical structural frame 'could be approximately 10–20% cheaper with the right selection' of grid and decking at early design stage.

3. Why Structural Efficiency Matters

Climate and Resource Imperatives

Structural efficiency changes the scale of the global decarbonization challenge. With the world expected to add around 230 billion m^2 of new construction over the coming decades - equivalent to adding a city the size of Paris every week - the amount of concrete and steel used will largely determine the future emissions of heavy industry (See Ref. 60).

With the current carbon intensity of 300-400 $kgCO_2eq/m^2$ that would be equivalent to 70-90 Gt of emissions (See Ref. 55; 60). This makes efficiency a front-loaded climate strategy: while many production-side technologies - from hydrogen-based steelmaking to carbon capture in cement, are still costly or pre-commercial, using less of these materials delivers immediate, guaranteed savings: reducing material usage via SE-informed design has demonstrated the potential for 100 CO_2eq kg/m^2, meaning a conservative 2/3 emission reduction close to 50 Gt of emissions by 2050.

Structural efficiency can also reshape the economics of industrial transition. By designing smarter rather than simply building more, countries can meet infrastructure and housing needs with lower material throughput, fewer natural resources, sometimes imported, smaller energy demand, and less capital locked into high-emission assets.

Reduced demand on virgin steel and clinker means less pressure on the vast build-out of renewable electricity, hydrogen, and CO_2 transport and storage infrastructure otherwise required for deep industrial decarbonization. In this sense, structural efficiency can act as a force multiplier, strengthening the impact of other mitigation measures across the construction value chain.

The benefits extend well beyond climate mitigation. They strengthen economic resilience by reducing dependence on imported raw materials and volatile fossil-energy inputs. They also create innovation and employment opportunities, from digital design tools and advanced manufacturing to modular prefabrication and circular-construction business models. For developing economies, where infrastructure demand is still growing rapidly, structural efficiency offers a pathway to build essential assets with a fraction of the material and emissions intensity that characterised industrialisation in the past century.

Systemic benefits at a glance:

1. Immediate climate impacts: Delivers reductions now, before new production technologies scale.
2. Smaller industrial transition: Lowers the amount of steel and cement capacity that must shift to low-CO_2 routes.
3. Economic efficiency: Avoids over-investment in emission intensive plants and stranded assets.
4. Resource security: Cuts reliance on imported ores, clinker, and fossil fuels while expanding local recycling loops.
5. Innovation pull: Spurs digital design, new materials, and modular construction technologies that in turn enable deeper efficiency.

In short, structural efficiency is not merely a metric; it is a strategic lever for sustainable industrial transformation. By reducing demand, it frees resources, lowers systemic risks, and ensures that the world's transition to climate-neutral industry can proceed faster and at lower cost. In this sense, structural efficiency does more than reduce emissions - it acts as a systemic enabler of circular, resource-positive construction, triggering positive feedback across industrial value chains.

> **Structural efficiency is industrial efficiency at the scale of cities. It links design intelligence with material responsibility, turning engineering decisions into climate action.**

4. Barriers to Achieving Industrial Efficiency

Despite global recognition of embodied-emission challenges, structural efficiency remains unmeasured and therefore unincentivized.

Towards a Structural Efficiency Classification System (SECS): Research proposed under the SECS framework indicates that a large share of structural material capacity is misused. Closing even part of this efficiency gap could substantially cut global demand for steel and cement, offering one of the most effective and immediate pathways to reduce embodied emissions while maintaining safety and functionality.

Current frameworks, whether building codes or sustainability certifications, such as LEED, BREEAM, EDGE, or DGNB, address operational energy or embodied emissions per unit of material, but do not account for the efficiency of total material use. A design that relies on "green" steel or low-clinker cement can still achieve high ratings, even when it uses significantly more material than necessary.

As a result:
1. No benchmarks for designers: Engineers lack a common standard to compare the efficiency of structural solutions or typologies. "Optimisation" in current tools often remains narrow in scope, focusing on individual components rather than minimizing total material use.
2. Performance-blind procurement: Public and private clients continue to tender based on specifications such as concrete strength class, rebar ratio, or floor span, rather than on material efficiency or CO_2 emissions per square meter of functional output.
3. Fragmented responsibility: Architects, engineers, contractors, and material suppliers typically optimize within their own silos, while cost-plus contracting rarely incentivizes integrated material efficiency.
4. Perverse cost signals: Decades of cheap concrete and steel relative to labour have made material-intensive designs economically attractive, while refurbishment and reuse face higher transaction costs and, in many countries, higher VAT than new builds.
5. Layered safety factors: Across design codes, insurance, and procurement, successive conservative safety margins accumulate. As Julian Allwood and Jonathan Cullen note in 'Sustainable Materials With Both Eyes Open', this "multiplication of safety factors along the production chain" inflates material use without enhancing safety.
6. Limited awareness and skills: Industry surveys highlight low familiarity with low-carbon structural options, with gaps in supply-chain skills and technical standards identified as the main barriers to adoption.

The result is a system structurally biased toward over-building. Without measurable indicators - such as a structural efficiency metric using structure-specific units like stress-volume, or embodied-emission targets per square metre of floor area - one of the most powerful levers for climate mitigation in construction remains invisible to policymakers and unaccounted for in design decisions.

In short, current regulations and standards reward cleaner materials, but not smarter structures. Establishing objective metrics for structural efficiency, and embedding them in building codes, procurement criteria, and certification schemes, is essential to transform efficiency from a niche engineering practice into a mainstream requirement.

5. Toward Global Standards and Tools

Realizing the potential of structural efficiency requires a coherent framework that makes it measurable, verifiable, and comparable. Just as energy efficiency gained momentum once governments and industries agreed on common performance metrics and labeling schemes in the 1970s, the construction sector today needs shared definitions, reference values, and verification systems to assess how efficiently a building uses materials to fulfill its structural function. A comprehensive approach can be organized around five mutually reinforcing pillars:

1. Standardization: Develop a voluntary international standard defining and quantifying structural efficiency, analogous to energy-efficiency classes. The paper 'Towards a Structural efficiency Classification System' (See Ref. 55) already proposes such a rating (Classes A–E) based on stress volume per m^2, comparing real structures to theoretical optima. This concept could be expanded under ISO or EN coordination to create a globally recognisable benchmark for "how efficiently a building carries its loads."
2. Scientific Validation and Data Aggregation: Consolidate global research and case studies to develop reference values by material type, structural category, and building function. Harmonised datasets would allow designers to benchmark new projects against typical, best-practice, and theoretical performance ranges.
3. Digital Integration: Embed efficiency metrics into Building Information Modelling and digital-twin platforms to enable real-time feedback on the material and emission implications of their choices during design. Standardised data schemes and open-source APIs would ensure that utilisation ratios and stress-volume indicators connect seamlessly to LCA and procurement modules.
4. Certification and Auditing: Establish third-party verification of structural efficiency performance. Independent audits (similar to energy-performance certificates) would let clients, financiers, and regulators compare tenders on a performance basis (efficiency class, stress volume/m^2 or kg CO_2/m^2) rather than just on prescriptive material specifications.
5. Professional training and institutional coordination: Develop targeted education modules for engineers, architects, and public-sector reviewers on the use of structural efficiency metrics, digital tools, and verification procedures.

UNIDO's work in the construction sector can support a platform for coordinating such standards, linking life-cycle analysis, digital innovation, and MEA implementation.

Together, these building blocks would make structural efficiency visible, verifiable, and investable, turning it from an engineering ideal into a mainstream performance criterion embedded in design, certification, and procurement.

Once common metrics and verification systems are established, the next challenge is to align market rules, finance, and innovation so that efficient design becomes the default choice rather than the exception.

6. From Concept to Practice: Policy, Finance, and Innovation

Delivering structural efficiency at scale requires mobilising the policy frameworks, financial mechanisms, and innovation systems that can turn technical potential into widespread practice. The transformation can build on three complementary pillars:

1. Policy and Standards: Make efficiency the default

A robust policy framework is essential to embed structural efficiency into mainstream construction practice. Establishing a recognised structural-efficiency standard provides a consistent method to calculate and compare performance across projects. Governments can accelerate market uptake by creating lead markets for low-CO_2 and low-material designs through public procurement, contracts-for-difference for low-carbon materials, and performance-based building codes that set embodied-carbon limits per square metre. Integrating structural-efficiency indicators - such as SECS classes alongside verified embodied-carbon intensities - into permitting systems, EN 15804/15978 assessments, and green-building certification ensures that efficiency becomes a formal criterion in project approval. Policy reform can further correct perverse incentives by aligning VAT, insurance practices, and safety-factor requirements to avoid unnecessary material use, while regulation of clean scrap streams, modularity, and component reuse strengthens end-of-life value chains and supports circular-economy objectives.

2. Finance: De-risk early adoption and scale

Finance plays a critical role in scaling structural efficiency by reducing risk and enabling early adoption. De-risking first-of-a-kind (FOAK) and early commercial projects through concessional finance, loan guarantees, and blended-finance facilities from public development banks can accelerate deployment and build confidence in innovative low-material solutions. Outcome-based procurement and pay-for-performance contracts further incentivise projects that demonstrate verified reductions in material usage and embodied carbon per square metre. At the same time, managing transition and stranded-asset risks requires linking capital-replacement cycles to low-material solutions and establishing disclosure requirements for embodied-carbon intensity in construction finance portfolios, ensuring that financial institutions support a shift toward more efficient and climate-aligned construction practices.

3. Innovation and Capability: Accelerate learning and diffusion

Strengthening innovation and capabilities is essential to accelerate learning and diffuse structural-efficiency practices across the construction sector. Mission-driven R&D and demonstration initiatives - ranging from generative-design optimisation to low-clinker binders such as LC^3, modular and reusable systems, and advanced analytics for design-for-disassembly, can establish practical pathways for material reduction. Scaling up "ready-now" SE-assessed low-carbon construction technologies (LCCTs) requires addressing real barriers such as standards, awareness, and supply-chain readiness identified in recent LCCT assessments. Mainstreaming digital tools and transparency, including BIM-based embodied-carbon reporting in planning approvals and open benchmarks of structural-utilisation performance by building type, further supports adoption. Combined with coherent action across policy and finance, these efforts help move structural efficiency from niche practice to market norm.

7. Building Strategically: The Future of Sustainable Construction

To build strategically is to build efficiently. Structural efficiency shows that sustainability begins not only with greener materials but with smarter design decisions that determine how much material is required from the outset. In this way, it reframes the construction challenge - not just how to decarbonize materials, but how to reduce the total quantity needed.

Reducing material demand is not a constraint - it is an act of innovation and foresight. By designing for verified, measured necessity rather than excess - focusing on function rather than surplus - the construction sector can simultaneously deliver resilience, affordability, and climate alignment. Every project that achieves more with less helps decouple economic growth from material throughput and reduces pressure on future clean-energy systems and industrial transitions.

IV. The Construction Sector and UNIDO’s Mandate for Inclusive and Sustainable Industrial Development

1. Strategic Relevance to ISID

A cornerstone of inclusive and sustainable industrial growth

Construction sits at the intersection of industry, environment, and society. It underpins manufacturing demand for cement, steel, glass, ceramics, paints, and insulation, while generating livelihoods for tens of millions of workers worldwide. In developing economies, the sector’s forward and backward linkages make it one of the most effective multipliers of local value addition, supporting small and medium-sized enterprises, building-materials industries, and auxiliary services.

For UNIDO, construction exemplifies Inclusive and Sustainable Industrial Development: it fosters inclusive employment, drives industrial diversification, and shapes the environmental sustainability of future growth. As custodian of SDG 9 (Industry, Innovation and Infrastructure), UNIDO positions construction as both a beneficiary and a driver of sustainable industrialization, advancing innovation, productivity, and low-emission competitiveness.

Chemicals and material efficiency as pivotal entry points

Among the many sustainability dimensions in construction, two stand out for their potential to deliver significant environmental and social gains. These are not isolated technical areas, but strategic levers that link industry performance with human and planetary well-being:

1. Chemicals and material health: Chemical additives have played an important role in delivering vital performance properties in the built environment, emerging through decades of innovation in the construction sector. Yet not all proved to be harmless, as demonstrated in the example of flame retardants containing PFAS - currently listed under the Stockholm Convention as industrial POPs. These chemicals can affect workers during production, occupants during use, and recyclers at end-of-life. Improving chemical safety and transparency across construction value chains can protect workers and communities, support circularity, and strengthen compliance with international chemicals-management frameworks - priorities closely aligned with UNIDO’s mandate on cleaner production and sustainable industrial development.

2. Design, structural and material efficiency: Optimizing building design, extending asset lifespans, and improving material efficiency and recovery can reduce embodied carbon by up to 40% and cut construction waste by 70% (See Ref. 50). These approaches contribute directly to industrial modernization by lowering production costs, stimulating innovation in low-carbon materials, and enhancing long-term competitiveness.

Structural optimisation, adaptive reuse, and the use of recycled aggregates can extend asset lifetimes while lowering costs and dependence on virgin resources. For developing economies, such efficiency offers pathways for industrial diversification, small and medium-sized enterprises (SMEs) greater participation, and job creation in green-building supply chains. Together, these entry points connect industrial, environmental, and social outcomes, making them central pillars of UNIDO’s construction agenda.

Circular Economy in Construction

> “In energy, the greenest kilowatt-hour is the one you don’t use. In construction, the greenest material is the one you design out.”
>
> **European Innovation Council**

Enablers of change

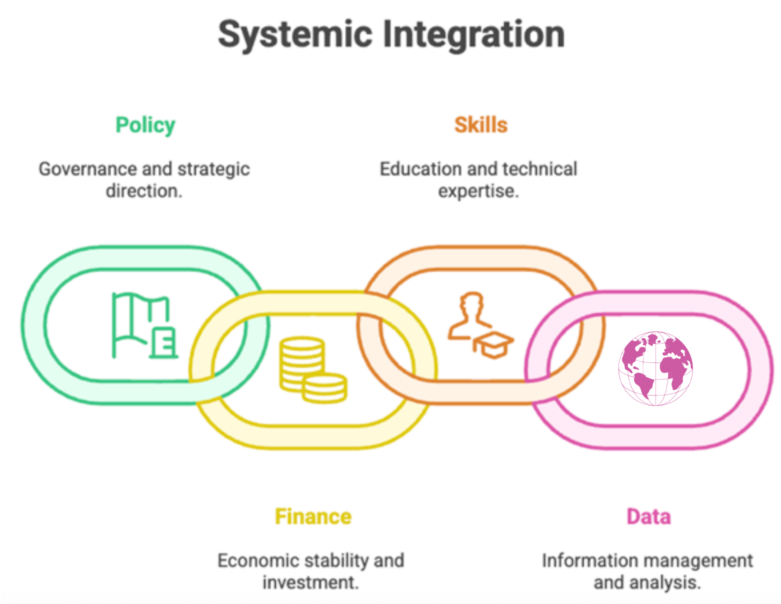
These transformations depend on coherent systems that connect:

1. Policy and standards: Green public procurement, fiscal incentives and performance-based standards for low-toxicity, circular materials.

2. Finance and market demand: Green bonds, ESG lending, blended-finance models and procurement commitments for climate-aligned infrastructure.

3. Skills and safety: Training workers and enterprises in digital, modular, circular and safe construction practices.

4. Data and digitalization: Interoperable BIM, digital-twin platforms, material passports, and life-cycle assessment tools to quantify embodied emissions, chemical content, and material flows. Together, these enablers shift sustainability from obligation to opportunity - a driver of productivity, innovation, and inclusive industrial development.



2. Synergies with MEAs and global funding mechanisms' priorities

Advancing global environmental commitments through construction

The construction sector provides tangible opportunities to operationalize the Multilateral Environmental Agreements (MEAs) for which UNIDO provides technical and policy support.

Through these linkages, construction becomes a delivery mechanism for MEA implementation, demonstrating how sustainable industrial practices can reinforce international environmental objectives.

Contribution to GEF focal areas

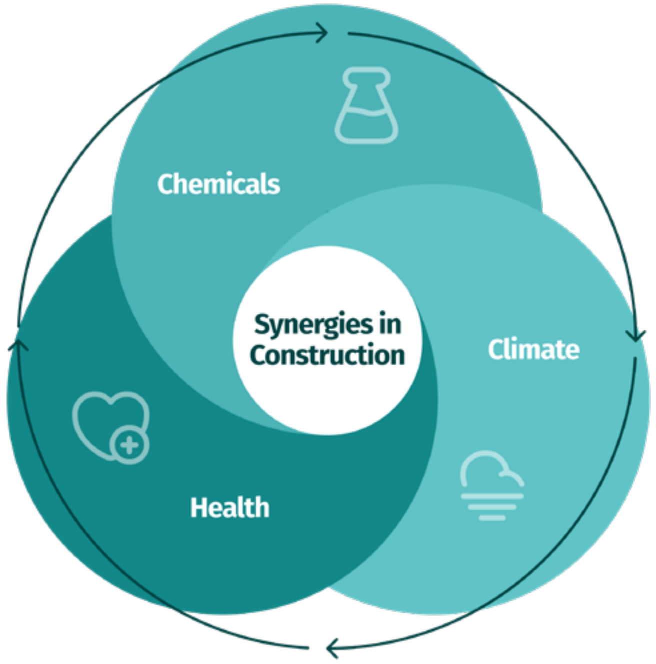
Construction interventions contribute simultaneously to three focal areas of the Global Environment Facility (GEF-9):

1. Chemicals and Waste: Detoxifying material supply chains, improving the safe recycling and management of construction and demolition waste, and preventing hazardous releases.

2. Climate Change Mitigation: Deploying low-carbon cements such as LC³, material-efficient design, and circular construction principles to reduce greenhouse-gas emissions.

3. Land degradation and Biodiversity: Reducing demand for virgin raw materials, limiting extraction pressures from quarrying and mining, and supporting reuse and circular value chains that lower impacts on land and ecosystems.

UNIDO's circular construction initiatives provide a practical framework for linking chemical safety, waste reduction, material efficiency and low-carbon construction, helping countries generate benefits across MEAs obligations and GEF programming priorities.



Illustrative UNIDO-supported examples

1. Costa Rica and Morocco (GEF Integrated Programme-11): Supporting green transformation of the construction supply chain through the promotion of safer alternatives to hazardous materials, circular approaches, life-cycle management, and enabling policy and market frameworks for sustainable construction.

2. Thailand: National initiative to decarbonize the cement and concrete sectors by aligning policy reform, innovation, and green public procurement to meet net-zero targets.

3. Caribbean Small Island Developing States (SIDS), Brazil, Philippines: Advancing low-emission and resource-efficient cement production through mercury-emission reduction measures, best available technologies and practices (BAT/BEP), clinker substitution, energy efficiency, circular approaches, and strengthened institutional and regulatory capacities.

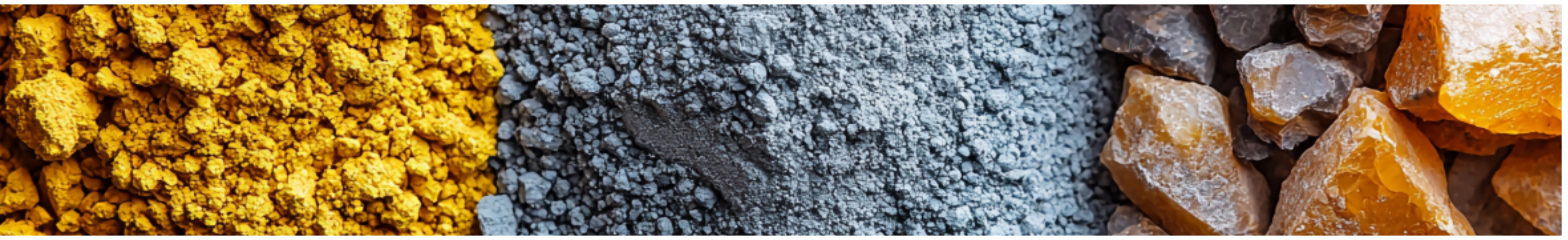
UNIDO Circular Construction Pilots

Brazil, Caribbean SIDS, Costa Rica,
El Salvador, Kyrgyzstan, Morocco,
Philippines, South Africa, Thailand

4. South Africa: Hospital chiller retrofit using low-global-warming-potential refrigerants, reducing energy costs and emissions while enhancing health-sector resilience.

5. El Salvador: Joint Programme on Housing and Productive, Sustainable Urban Settlements (2009-2012). A participatory diagnosis of the social-housing value chain led to SME training, mobile construction schools, and supply-chain aggregation, reducing costs and improving quality. This early example showed how inclusive industrial policy and capacity building can translate sustainability objectives into local economic development.

6. Kyrgyzstan: Introduction of eco-friendly, cost-effective building materials using local raw inputs, boosting rural entrepreneurship and resilience to climate impacts.



3. UNIDO Support Pathways for Member States

Policy and MEA Support

UNIDO assists governments in embedding MEA obligations into national construction policies and standards by:
1. Translating Stockholm, Minamata, and GFC commitments into national building regulations, product standards and compliance mechanisms;
2. Supporting the development of Extended Producer Responsibility (EPR) schemes and green procurement frameworks;
3. Strengthening institutional and analytical capacities for life-cycle management, monitoring, and reporting;
4. Supporting the integration of digital tools, material passports, and traceability systems into permitting and construction-governance frameworks;
5. Facilitating regional harmonization of standards and knowledge exchange to accelerate market uptake of low-carbon and non-toxic construction practices.

Cleaner and Safer Value Chains

UNIDO's technical cooperation promotes low-emission and non-toxic materials across the construction life cycle:
1. Demonstrating low-carbon technologies, including LC^3 cements, alternative binders, co-processing, waste-heat recovery, and carbon-capture utilization and storage (CCUS) in cement plants;
2. Supporting enterprises in replacing POP-containing inputs and improving waste segregation and recycling;
3. Developing national and regional standards, certification schemes, and quality-assurance systems for circular and low-carbon construction materials;
4. Supporting SMEs and local manufacturers in adopting cleaner production methods, resource-efficient technologies, and environmental management systems;
5. Promoting modular construction, design for disassembly, and secondary-material markets to strengthen circular value chains.

Chemicals and Worker Health

1. Implementing occupational-safety programmes, exposure monitoring and risk management;
2. Developing training modules on safe chemical handling, substitution practices and waste management;
3. Integrating gender-responsive occupational health and safety measures;
4. Promoting low-emission materials and ventilation design to improve indoor air quality;
5. Strengthening awareness and technical capacity among workers, enterprises, and regulators on chemical risks across construction supply chains.

Innovation and Partnerships

UNIDO leverages its convening power and strategic partnerships to accelerate innovation in the construction sector:
1. Drawing on relevant international initiatives and platforms, including the Global Alliance for Buildings and Construction (GlobalABC), and the World Green Building Council, to inform knowledge exchange and approaches to metrics and standards;
2. Supporting digitalization, BIM, and AI-enabled tools to monitor material flows and embodied emissions;
3. Mobilizing green finance and ESG-aligned investments through blended-finance instruments and public-private partnerships;
4. Facilitating South-South cooperation and technology transfer on circular materials and energy-efficient systems.

Call for Action: The measure of progress can no longer be just how much we build, but how responsibly we build it.

4. Moving Forward: Perspectives and Options

The transformation of construction is not a single project but an evolving collaboration between policy makers, industry, and financiers. UNIDO's contribution lies in enabling countries to translate sustainability commitments into practical industrial pathways - demonstrating that low-carbon, non-toxic, and resource-efficient construction can also be competitive, inclusive, and job-rich.

Emerging country priorities point to several areas where targeted support will be needed in the near future:

1. Integration of construction into national ISID strategies and embedding sustainable-building targets and circular-economy principles within industrial and urban-development plans.
2. Expanding the MEA-aligned technical assistance to provide capacity building for compliance, reporting, and chemicals substitution.
3. Fostering of innovation ecosystems and linking R&D, start-ups, and SMEs to circular-construction opportunities and digital tools.
4. Promoting inclusive skills development, with training for workers - especially women and youth - in safe, digital, and green construction techniques.
5. Mobilizing finance for transformation by engaging development banks, investors, and city authorities to channel capital toward low-emission, circular infrastructure.

UNIDO's ongoing projects already embody these principles: each example demonstrates that when policy, technology, and capacity align, construction becomes a visible champion of ISID - transforming risks into engines of prosperity.

For each country, the path to sustainable construction will differ.

Choices around materials, affordability, and performance must reflect local realities, from housing needs and climatic conditions to industrial capacity and resource availability.

The role of institutions such as UNIDO is to help countries identify and prioritize the solutions most relevant to their national context, ensuring progress that is both sustainable and inclusive.

Conclusion

Together, these enablers shift sustainability from obligation to opportunity, a driver of productivity, innovation, and inclusive industrial development. As earlier chapters highlighted, improving structural and material efficiency by designing buildings to use fewer resources, while delivering the same function, represents a powerful complement to these transformations.

A new foundation for cooperation

The transformation of construction is not only a technical option, but a collective responsibility. Aligning industrial policy, climate finance, and innovation can shift the sector from one defined by extraction and waste to one characterized by efficiency, safety, and regeneration.

Across regions, practical models are already taking shape - from UNIDO-supported circular materials initiatives in North Africa to collaborative efforts on sustainable industrial parks and green building supply chains. These examples demonstrate how partnerships can bridge policy and practice, turning sustainability from aspiration into an industry standard.

By focusing on two pivotal levers - chemicals management and material efficiency - countries and industries can build infrastructure that sustains economies, protects people, and restores the planet.

The foundations of tomorrow's prosperity will be measured not by how much we build, but by how responsibly we build it. These principles can guide the partnerships, policy actions and implementation pathways needed to turn ambition into lasting impact.

For each country, the path to sustainable construction will differ. Choices around materials, affordability, and performance must reflect local realities - from housing needs and climatic conditions to industrial capacity and resource availability. The role of institutions such as UNIDO is to help countries identify and prioritize the solutions most relevant to their national context, ensuring progress that is both sustainable and inclusive.

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Vienna International Centre
Wagramerstr. 5, P.O. Box 300,
A-1400 Vienna, Austria

☎ +43 1 26026-0

www.unido.org

✉ unido@unido.org

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