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Circular Manufacturing in Saudi Arabia and the MENA Region: An Industrial Systems Engineering Framework for Unlocking Circular Economy Climate Potential

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Abstract

Industrialization in Saudi Arabia and the wider Middle East and North Africa (MENA) region is central to economic diversification, but is also a major and growing source of greenhouse gas (GHG) emissions. Saudi Arabia alone accounted for around 535 Mt CO_2 of energy-related emissions in 2023, about 1.5% of global CO_2 from fuel combustion, with industry representing the largest share of domestic energy-related emissions. Conventional decarbonization strategies focusing on low-carbon energy are necessary but insufficient: analyses by the Ellen MacArthur Foundation indicate that even a fully decarbonized energy system would address only about 55% of global emissions, with the remaining 45% linked to how materials and food are produced and used. The same study estimates that circular strategies in cement, steel, aluminum, plastics and food systems could eliminate about 9.3 Gt CO_2e of production-related emissions globally by 2050. This paper adapts these circular economy insights to the context of Saudi Arabia and the MENA region, developing an industrial systems engineering framework for circular manufacturing transitions. Using Saudi industrial emissions data—where industry accounts for roughly 230 Mt CO_2 (about 46% of national CO_2) and regional material and waste statistics (including very high per-capita polymer consumption, high municipal solid waste generation with low recycling rates, and food loss and waste around 28–33%). General Food Security Authority 2020, Ministry of Municipal and Rural Affairs and Housing 2020, the paper maps intervention points along key value chains (steel, cement, aluminum, plastics and food systems) and construct qualitative scenarios to 2050. Scaling the Ellen MacArthur Foundation's global circular mitigation potential in proportion to Saudi Arabia's high industrial share of global emissions suggests that circular manufacturing strategies in these sectors could plausibly reduce Saudi production-related emissions by on the order of 140–190 Mt CO_2e per year by mid-century, in addition to energy-sector decarbonization. At the wider MENA scale, proportional scaling suggests a potential of around 0.6–0.9 Gt CO_2e annually by 2050. The framework is presented through a holistic system diagram of linear and circular configurations, and a Sankey-style visualization of how globally estimated circular mitigation potential can be apportioned to Saudi Arabia and the MENA region. The paper concludes by discussing how these circular manufacturing pathways interact with national and regional strategies, including Saudi Vision 2030, the Circular Carbon Economy framework, the Saudi Green Initiative and emerging Industry 5.0 agendas, and outlines a research agenda for country-specific modelling and just transition strategies in resource-rich, industrializing economies.

Keywords
Circular economy; Sustainable manufacturing; Industrial systems engineering; Saudi Arabia; MENA; Climate mitigation; Industry 5.0

1. Introduction

Saudi Arabia and the wider Middle East and North Africa (MENA) region are simultaneously highly vulnerable to climate change and disproportionately emissions-intensive. Near-surface temperatures in the Arab region are increasing faster than the global average, and extreme heat and drought already threaten water security, food systems and human health (ESCWA 2022). At the same time, the region emitted about 3.2 Gt CO_2 in 2018, around 8–9% of global greenhouse gas emissions, largely driven by fossil-fuel-based energy systems (ESCWA 2022, International Energy Agency 2023).
Within this regional picture, Saudi Arabia plays a pivotal role. Energy-related CO_2 emissions are around 535 Mt per year, corresponding to roughly 1.5% of global CO_2 from fuel combustion, while per-capita emissions are among the highest in the world (International Energy Agency 2023). Industrial activities—dominated by iron and steel, cement, aluminium, chemicals and fertilisers—account for about 230 Mt CO_2, or roughly 46% of national energy-related emissions (KAPSARC 2020). The Kingdom has announced an ambition to reach net-zero greenhouse gas emissions by 2060 and has committed to an annual reduction of 278 Mt CO_2e by 2030 under its updated Nationally Determined Contribution (NDC), within the umbrella of the Saudi Green Initiative and the Circular Carbon Economy (CCE) framework (Government of Saudi Arabia 2021a, Government of Saudi Arabia 2021b).

While decarbonisation of power and fuels is central to these commitments, the material side of the economy—how products and materials are designed, used and circulated—remains comparatively underdeveloped in policy and practice. Analyses by the Ellen MacArthur Foundation show that even with full decarbonisation of energy supply, around 45% of global emissions would remain linked to material production and land use, and that circular economy strategies in cement, steel, aluminium, plastics and food systems could eliminate about 9.3 Gt CO_2e of production-related emissions annually by 2050 (Ellen MacArthur Foundation 2019). For Saudi Arabia and MENA, where material throughput and waste generation are high and industrialisation is ongoing, circular manufacturing therefore represents a critical complement to energy-focused climate strategies (Lieder and Rashid 2016, Patwa et al. 2021, ESCWA 2023).

The research question addressed in this paper is: how can Saudi Arabia and the MENA region harness circular economy strategies in manufacturing grounded in global circular economy analyses to achieve deep emissions reductions while supporting economic diversification and resilience? An industrial systems engineering lens is adopted to translate circular principles into concrete intervention points along manufacturing value chains and to construct illustrative scenarios for circular manufacturing transitions in a representative middle-income, resource-rich context. In line with emerging Industry 5.0 thinking, the framework emphasises not only environmental performance but also resilience and human-centric industrial development (Breque et al. 2021).

2. Literature Review

The circular economy is widely defined as an economic system that is restorative and regenerative by design, aiming to keep products, components and materials at their highest utility and value for as long as possible (Ellen MacArthur Foundation 2013). The Ellen MacArthur Foundation articulates three core principles: design out waste and pollution, keep products and materials in use, and regenerate natural systems (Ellen MacArthur Foundation 2019). Early Ellen MacArthur Foundation reports combined product case studies with economy-wide analysis and showed that adopting circular strategies across a subset of European manufacturing could yield substantial material cost savings, reduce dependence on virgin resources and stimulate innovation (Ellen MacArthur Foundation 2013, Ellen MacArthur Foundation 2015).

Subsequent work has emphasised the climate relevance of circularity. In Completing the Picture: How the Circular Economy Tackles Climate Change, the Ellen MacArthur Foundation quantified how circular strategies in cement, steel, aluminium, plastics and food could almost halve global production-related emissions by 2050 relative to a linear trajectory, equivalent to about 9.3 Gt CO_2e annually (Ellen MacArthur Foundation 2019). This positions the circular economy as a critical complement to energy-sector decarbonisation rather than a substitute for it (Lieder and Rashid 2016, Patwa et al. 2021).

In parallel, the Industry 5.0 paradigm has emerged as a forward-looking vision for industrial development that is sustainable, human-centric and resilient (Breque et al. 2021). Industry 5.0 complements Industry 4.0's focus on digitalisation and automation by explicitly recognising the importance of environmental sustainability, worker wellbeing and system robustness to shocks. Circular economy strategies in manufacturing—such as design for durability, repair, reuse and remanufacturing; high-quality recycling; and bio-based materials—provide concrete pathways to operationalise the sustainability dimension of Industry 5.0, while reverse logistics, digital product passports and data-driven material flow management connect to its digital and resilience pillars (Breque et al. 2021, Lieder and Rashid 2016).

In the Arab region, material consumption and waste generation have risen rapidly. The material footprint per capita has increased to around 12 t per year, while many countries face acute water scarcity, land degradation and food security challenges (ESCWA 2022, ESCWA 2023). In Saudi Arabia, polymer consumption exceeds 95 kg per capita per year, driven largely by packaging and construction, and municipal solid waste generation is around 1.7 kg per capita per day (GCC Petrochemicals and Chemicals Association 2019, Ministry of Municipal and Rural Affairs and Housing 2020). Recycling rates for plastic, metal and paper remain low—on the order of 3–5%—despite a Vision 2030 target to raise the national recycling rate to at least 35% (ESCWA 2023, Ministry of Municipal and Rural Affairs and Housing 2020). Food loss and waste (FLW) are also high: national estimates suggest a combined FLW rate of about 33%, equivalent to roughly 184 kg of food per capita per year and economic losses in the tens of billions of Saudi riyals (General Food Security Authority 2020).

These characteristics indicate that Saudi Arabia and MENA exhibit high throughput of primary materials and food, with relatively low circularity (ESCWA 2022, ESCWA 2023). At the same time, ongoing industrialisation and large-scale infrastructure projects, such as the Vision 2030 "giga-projects", create a window of opportunity to embed circular principles into new assets, industrial parks and logistics systems from the outset (Ellen MacArthur Foundation 2015, ESCWA 2023). This context motivates the development of a systems engineering framework tailored to Saudi and regional conditions, explicitly positioned as a concrete implementation pathway for the sustainability dimension of Industry 5.0 in the manufacturing domain (Breque et al. 2021).

3. Methods

The work was mainly a desktop research looking into historical public data. An industrial systems engineering approach is adopted to represent the Saudi manufacturing system as a network of process nodes connected by material and energy flows (Lieder and Rashid 2016). The focus is on five priority value chains where circular strategies have particularly large global mitigation potential and strong relevance in the Saudi and MENA context: steel, cement, aluminium, plastics and food systems (Ellen MacArthur Foundation 2019, Patwa et al. 2021).

Each process node for example, steelmaking, cement clinker production, polymerisation, food processing and packaging is characterised by input material composition (virgin and secondary), process technology and energy sources, yields and scrap rates, by-product and emission profiles, and basic economic indicators such as costs and value added (Lieder and Rashid 2016). The system boundary includes upstream resource extraction (where domestic), core manufacturing and secondary processing, and downstream end-of-life options (reuse, repair, remanufacturing, recycling, energy recovery and disposal). Regional trade flows in materials and products are treated as exogenous in the illustrative scenarios, but the framework can be extended to endogenise them.

Figure 1 provides a holistic visual representation of this framework. Panel (a) depicts the current linear configuration in Saudi Arabia and MENA, in which domestic and imported resources feed energy-intensive manufacturing sectors and most post-use materials flow to landfill or uncontrolled disposal. Panel (b) overlays circular intervention points along the same value chains, illustrating where secondary materials loops, organic valorisation and governance layers (e.g. Vision 2030, Circular Carbon Economy, regional circular agendas) interact with core manufacturing processes. In this sense, Figure 1 operationalises the systems engineering framework by linking process-level interventions to system-wide flows and policy levers.

4. Data Collection

Baseline material and emissions flows are calibrated using available national and regional statistics. At the national level, energy and sectoral emissions data indicate industrial CO_2 emissions of about 230 Mt in 2019—around 46% of Saudi energy-related emissions—and data on polymer consumption, municipal solid waste generation and food loss and waste are used to characterise key downstream flows (GCC Petrochemicals and Chemicals Association 2019, KAPSARC 2020, International Energy Agency 2023, General Food Security Authority 2020, Ministry of Municipal and Rural Affairs and Housing 2020). At the regional level, estimates of the MENA share of global CO_2 and greenhouse gas emissions, as well as material footprint and food loss and waste metrics, are used to situate the Saudi case within wider regional patterns (ESCWA 2022, ESCWA 2023, FAO 2021). These data underpin the stylised material flows in Figure 1 and the scenario trajectories in Figure 2.

Key Saudi and MENA input data used to parameterise baseline flows and to scale the circular mitigation potential are summarised in Table 1. These include national and regional CO_2 and greenhouse gas emissions, sectoral emissions for Saudi industry, per-capita polymer consumption, municipal solid waste generation and recycling rates, and food loss and waste indicators (ESCWA 2022, ESCWA 2023, FAO 2021, GCC Petrochemicals and Chemicals Association 2019, KAPSARC 2020, International Energy Agency 2023, General Food Security Authority 2020, Ministry of Municipal and Rural Affairs and Housing 2020). To complement the tabular view, Figure 3 translates the circular mitigation-related entries into a waterfall diagram that shows how the Ellen MacArthur Foundation's global 9.3 Gt CO_2e circular potential can be apportioned to Saudi Arabia, the wider MENA region and the rest of the world based on their shares of global emissions (Ellen MacArthur Foundation 2019, ESCWA 2022, International Energy Agency 2023).

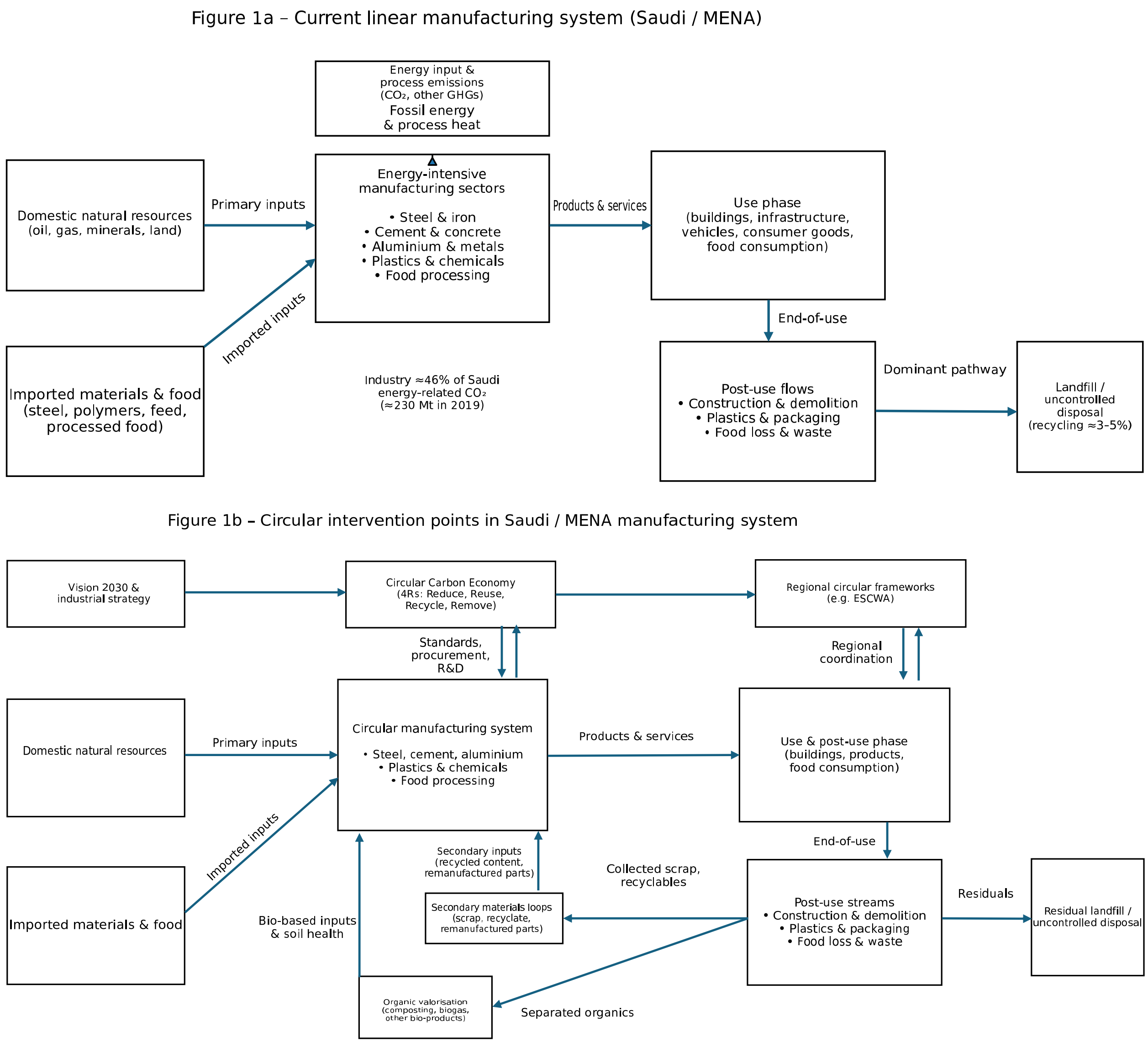

Figure 1. Holistic systems engineering framework for Saudi and MENA manufacturing: (a) current linear configuration; (b) circular intervention points along priority value chains.

To construct emission trajectories, three stylised scenarios to 2050 are defined. In the linear lock-in scenario, industrial emissions grow modestly from 230 Mt CO_2 in 2019 to around 270 Mt in 2050, reflecting continued material demand growth with limited circularity (KAPSARC 2020). In the partial circular adoption scenario, incremental efficiency and circular measures—such as moderate increases in recycling and modest reductions in FLW—lead to a slight decline to around 210 Mt CO_2 by 2050 (ESCWA 2023, General Food Security Authority 2020). In the strategic circular transition scenario, ambitious circular manufacturing strategies in the five focus value chains are combined with energy-sector decarbonisation, driving industrial emissions down to around 80 Mt CO_2 by 2050 (Ellen MacArthur Foundation 2019, Lieder and Rashid 2016). The time paths are represented as linear interpolations between these endpoints and are intended to indicate orders of magnitude and relative differences rather than precise forecasts.

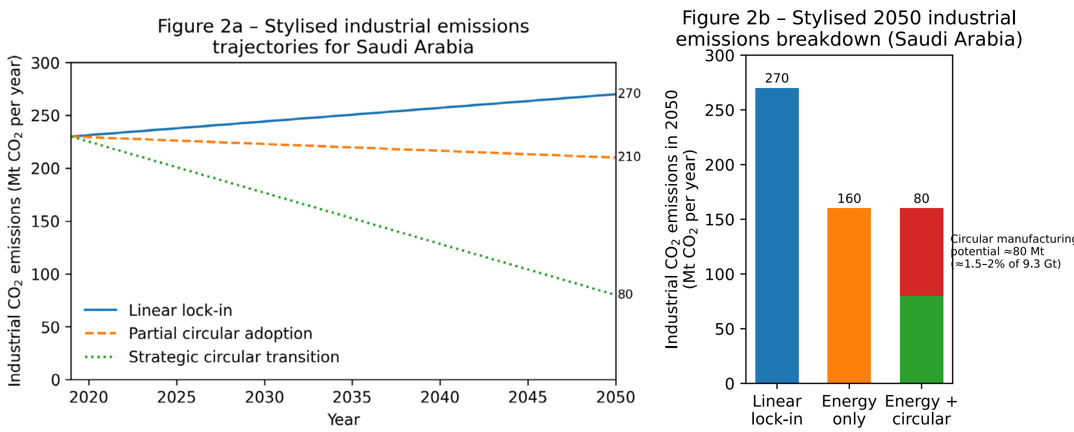

Figure 2. Stylized industrial emissions trajectories and 2050 breakdown for Saudi industrial CO_2 emissions under three scenarios (linear lock-in, energy only, and energy plus circular manufacturing).

To approximate the national circular mitigation potential in the strategic scenario, the Ellen MacArthur Foundation's global estimate that circular strategies in cement, steel, aluminium, plastics and food systems could avoid about 9.3 Gt CO_2e per year by 2050 is scaled using Saudi and MENA shares of global emissions (Ellen MacArthur Foundation 2019, ESCWA 2022, ESCWA 2023, International Energy Agency 2023). Given that Saudi Arabia accounts for roughly 1.5% of global CO_2 from fuel combustion, and that industry represents a larger share of its emissions than the global average (KAPSARC 2020, International Energy Agency 2023), it is assumed that the Kingdom could realistically access 1.5–2.0% of the global circular mitigation potential in these sectors by mid-century. This implies an illustrative national circular mitigation range of approximately 140–190 Mt CO_2e per year by 2050. For the wider MENA region, which accounts for about 5.8% of global CO_2 from combustible fuels and around 8.7% of global greenhouse gas emissions, a potential of 6–10% of the global circular mitigation in these value chains is assumed, corresponding to 0.6–0.9 Gt CO_2e per year by 2050 (ESCWA 2022, ESCWA 2023, International Energy Agency 2023).

Table 1. Summary of key Saudi and MENA input data used in circular manufacturing scenarios

Parameter	Region / country	Approximate value (unit)	Notes / source
Total energy-related CO_2 emissions	Saudi Arabia	≈ 535 Mt CO_2 (2023)	IEA / international datasets on fuel-combustion CO_2 , International Energy Agency (2023).
Share of global CO_2 from fuel combustion	Saudi Arabia	≈ 1.5%	Calculated from Saudi and global CO_2 emissions (International Energy Agency 2023).
Industrial CO_2 emissions (energy-related)	Saudi Arabia	≈ 230 Mt CO_2 (≈ 46% of national CO_2, 2019)	Sectoral breakdown including iron and steel, cement, aluminium, chemicals and fertilisers (KAPSARC 2020).
Material footprint per capita	Arab region (MENA)	≈ 12 t per capita per year	ESCWA analysis of regional material footprint trends (ESCWA 2022, ESCWA 2023).

Share of global GHG emissions	MENA region	≈ 8.7%	ESCWA regional climate assessment (ESCWA 2022).
Share of global CO_2 from combustible fuels	MENA region	≈ 5.8%	ESCWA and International Energy Agency regional estimates (ESCWA 2022, International Energy Agency 2023).
Polymer consumption per capita	Saudi Arabia	> 95 kg polymers per capita per year	GCC polymer consumption report; KSA ≈ 61% of GCC polymer use (GCC Petrochemicals and Chemicals Association 2019).
Municipal solid waste (MSW) generation per capita	Saudi Arabia	≈ 1.7 kg per capita per day	National MSW generation statistics (Ministry of Municipal and Rural Affairs and Housing 2020).
Recycling rate (overall waste)	Saudi Arabia	≈ 3–5% of plastic, metal and paper waste	National circular economy baseline; most waste landfilled (ESCWA 2023, Ministry of Municipal and Rural Affairs and Housing 2020).
Vision 2030 target for municipal recycling	Saudi Arabia	≥ 35% of waste recycled by 2030	Vision 2030 waste management target (ESCWA 2023, Government of Saudi Arabia 2021a).
Food loss and waste (FLW) rate	Saudi Arabia	≈ 33% total (14.2% loss, 18.9% waste)	Saudi food loss and waste index; national assessment (General Food Security Authority 2020).
FLW per capita	Saudi Arabia	≈ 184 kg food per capita per year	Same index; large economic losses annually (General Food Security Authority 2020).
Typical food loss between post-harvest and retail	MENA region	≈ 15%	FAO regional FLW estimates (FAO 2021).
Food waste at retail and household	MENA region	≈ 75–163 kg per capita per year	FAO and regional studies on FLW (FAO 2021, ESCWA 2023).
Global circular mitigation potential (5 sectors)	Global	≈ 9.3 Gt CO_2 per year by 2050	Ellen MacArthur Foundation estimate for cement, steel, aluminium, plastics and food systems (Ellen MacArthur Foundation 2019).
Saudi share of global circular potential	Saudi Arabia	≈ 140–190 Mt CO_2 per year by 2050	Assumed 1.5–2% of 9.3 Gt based on Saudi share of global CO_2 and industrial intensity (Ellen MacArthur Foundation 2019, KAPSARC 2020, International Energy Agency 2023).
MENA share of global circular potential	MENA region	≈ 0.6–0.9 Gt CO_2 per year by 2050	Assumed 6–10% of 9.3 Gt based on regional shares of global CO_2 and GHGs (Ellen MacArthur Foundation 2019, ESCWA 2022, ESCWA 2023, International Energy Agency 2023).

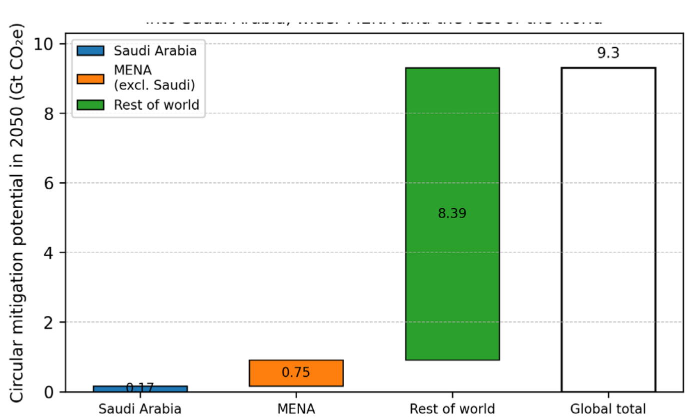

Figure 3. Waterfall breakdown of global circular mitigation potential into Saudi Arabia, wider MENA and rest of the world

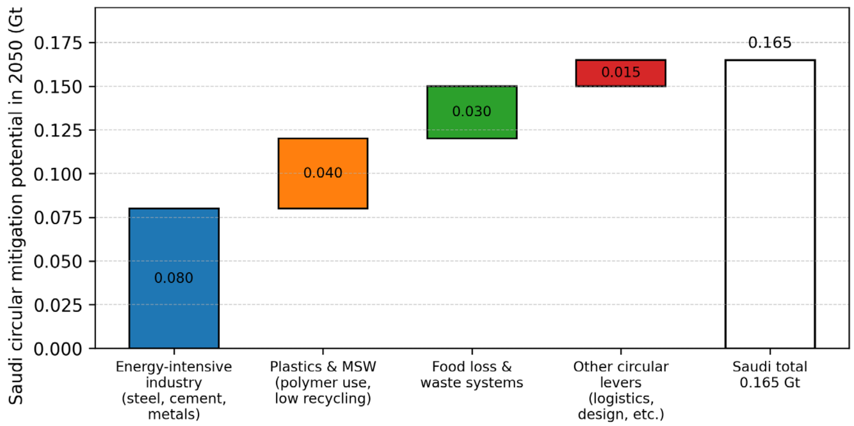

Figure 4. Waterfall breakdown of Saudi Arabia circular mitigation potential into contribution from industrial, waste, and food systems

5. Results and Discussion

5.1 Results: Illustrative Circular Manufacturing Scenarios

Figure 1 summarises the systems engineering framework applied to Saudi and MENA manufacturing. Panel (a) shows a linear configuration in which domestic and imported resources feed energy-intensive manufacturing sectors—steel, cement, aluminium, plastics and food processing—with most post-use materials and food losses flowing to landfill or uncontrolled disposal (ESCWA 2022, ESCWA 2023, GCC Petrochemicals and Chemicals Association 2019, Ministry of Municipal and Rural Affairs and Housing 2020). Panel (b) overlays circular intervention points aligned with Saudi Vision 2030, the Circular Carbon Economy framework and emerging regional circular economy agendas (Ellen MacArthur Foundation 2015, ESCWA 2023, Government of Saudi Arabia 2021a, Government of Saudi Arabia 2021b). These intervention points include high-quality scrap and structural steel reuse, clinker substitution and concrete recycling, closed-loop aluminium scrap systems, redesign and high-value recycling of plastics and packaging, improved cold chains and logistics to reduce food loss and waste, and organic waste valorisation through composting and bioenergy (Ellen MacArthur Foundation 2019, Lieder and Rashid 2016, FAO 2021, General Food Security Authority 2020).

Figure 2 presents stylised industrial emissions trajectories to 2050 under the three scenarios. In the linear lock-in scenario, industrial CO_2 emissions rise from 230 Mt in 2019 to roughly 270 Mt by 2050, reflecting continued growth in material demand with only incremental improvements (KAPSARC 2020). In the partial circular adoption scenario, incremental circular and efficiency measures lead to a modest decline to about 210 Mt CO_2 by 2050 (ESCWA 2023, KAPSARC 2020). In the strategic circular transition scenario, circular manufacturing in the five focus value chains is scaled in line with the nationally scaled share of the global circular mitigation potential and combined with energy-sector decarbonisation, resulting in industrial emissions of around 80 Mt CO_2 by 2050 (Ellen MacArthur Foundation 2019, Lieder and Rashid 2016).

Figure 3 and 4 complements Table 1 by providing a visual representation of how the globally estimated circular mitigation potential can be apportioned to Saudi Arabia and the MENA region. The diagram highlights that, under the assumptions used, Saudi Arabia could access on the order of a few hundred million tonnes of CO_2e of circular mitigation annually by 2050, while the wider MENA region could access on the order of several hundred million tonnes. This underscores the strategic importance of circular manufacturing pathways in regional climate and development agendas (Ellen MacArthur Foundation 2019, ESCWA 2022, ESCWA 2023, KAPSARC 2020, International Energy Agency 2023).

5.2 Discussion and Policy Implications

The analysis yields three main messages for Saudi Arabia and the MENA region. First, circular manufacturing is indispensable for deep decarbonisation in resource-rich, industrialising economies. Even under ambitious energy transitions, a large share of residual emissions will remain embedded in material production and food systems (Ellen

MacArthur Foundation 2019, Lieder and Rashid 2016, Patwa et al. 2021). Integrating circular strategies into industrial and infrastructure planning now can avoid decades of lock-in to linear, high-carbon assets and help align industrial development with national emissions targets (Ellen MacArthur Foundation 2015, ESCWA 2023, KAPSARC 2020).

Second, a systems-engineering perspective is essential. Circular economy discussions often focus on individual technologies or business models, but effective implementation requires coordinated changes across value chains, including product design, standards, infrastructure, reverse logistics and data systems (Lieder and Rashid 2016, Patwa et al. 2021). The framework and holistic diagrams presented in Figures 1–4 demonstrate how material flow analysis, process-level emissions modelling and simple scenario scaling can be combined to reveal leverage points in Saudi and regional manufacturing systems (Lieder and Rashid 2016, KAPSARC 2020, ESCWA 2023).

Third, the proposed framework aligns closely with the emerging Industry 5.0 paradigm, which emphasises sustainability, human-centricity and resilience alongside productivity (Breque et al. 2021). Circular manufacturing contributes to the sustainability dimension by reducing resource use and emissions, while design for durability, repairability and reuse can enhance worker safety and product quality. Digital tools for tracking materials, such as product passports and advanced analytics, can strengthen resilience by improving visibility and flexibility in supply chains (Breque et al. 2021, Patwa et al. 2021). In the Saudi and MENA context, positioning circular manufacturing transitions explicitly within Industry 5.0 strategies could help align industrial policy, research funding and skills development.

For policymakers, several priorities emerge. Circular manufacturing should be embedded into Vision 2030 implementation, especially within giga-projects and export-oriented manufacturing initiatives, through design-for-circularity standards, high recycled content requirements and green public procurement (Ellen MacArthur Foundation 2015, ESCWA 2023, Government of Saudi Arabia 2021a, Government of Saudi Arabia 2021b). The Circular Carbon Economy framework can be broadened to incorporate explicit material circularity indicators, and regional bodies such as ESCWA can play an important role in harmonising standards and supporting cross-border industrial symbiosis, for example through shared scrap markets and regional recycling infrastructure (ESCWA 2022, ESCWA 2023). Finally, circular transitions should be designed as just transitions, with attention to workers in carbon-intensive sectors and informal waste pickers, through retraining, social protection and inclusive governance mechanisms (Patwa et al. 2021, ESCWA 2022, ESCWA 2023).

6. Conclusion

An industrial systems engineering framework has been developed to explore the circular economy potential of manufacturing systems in Saudi Arabia and the MENA region, drawing on the Ellen MacArthur Foundation's global analyses of circular mitigation in cement, steel, aluminium, plastics and food systems (Ellen MacArthur Foundation 2013, Ellen MacArthur Foundation 2015, Ellen MacArthur Foundation 2019). By integrating baseline material and emissions data with stylised circular intervention modules and simple scaling of global mitigation potentials, illustrative scenarios have been constructed that situate circular manufacturing as a material contributor to national and regional climate strategies (Lieder and Rashid 2016, Patwa et al. 2021, ESCWA 2022, ESCWA 2023, KAPSARC 2020, International Energy Agency 2023, General Food Security Authority 2020, Ministry of Municipal and Rural Affairs and Housing 2020).

The results suggest that ambitious circular manufacturing strategies could reduce Saudi production-related emissions by on the order of 140–190 Mt CO_2e per year by 2050, in addition to energy-sector decarbonisation, and that the wider MENA region could potentially realise 0.6–0.9 Gt CO_2e of circular mitigation in the same value chains (Ellen MacArthur Foundation 2019, ESCWA 2022, ESCWA 2023, KAPSARC 2020, International Energy Agency 2023). While the scenarios are intentionally simplified and do not substitute for detailed optimisation models, they highlight the need to integrate circular economy thinking into industrial policy, infrastructure planning and climate governance, and to link such efforts explicitly to Industry 5.0 agendas (Breque et al. 2021, Patwa et al. 2021, ESCWA 2023). Future research should develop high-resolution country-specific models, explore the socio-technical dynamics of circular manufacturing transitions and quantify distributional and employment impacts to support just and effective circular industrial strategies in Saudi Arabia and across MENA (Patwa et al. 2021, ESCWA 2022, ESCWA 2023).

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References
Breque, M., De Nul, L., and Petridis, A., Industry 5.0: Towards a Sustainable, Human-Centric and Resilient European Industry, EU Research and Innovation Policy Paper, Publications Office of the European Union, Luxembourg, 2021.
ESCWA (United Nations Economic and Social Commission for Western Asia), The Arab Region and the Challenge of Climate Change, ESCWA, Beirut, 2022.
ESCWA (United Nations Economic and Social Commission for Western Asia), The Circular Economy in the Arab Region: Opportunities and Challenges, ESCWA, Beirut, 2023.
Ellen MacArthur Foundation, Completing the Picture: How the Circular Economy Tackles Climate Change, Ellen MacArthur Foundation, Cowes, UK, 2019.
Ellen MacArthur Foundation, Growth Within: A Circular Economy Vision for a Competitive Europe, Ellen MacArthur Foundation, SUN and McKinsey & Company, Cowes, UK, 2015.
Ellen MacArthur Foundation, Towards the Circular Economy, Vol. 1: An Economic and Business Rationale for an Accelerated Transition, Ellen MacArthur Foundation, Cowes, UK, 2013.
FAO (Food and Agriculture Organization of the United Nations), Near East and North Africa Regional Overview of Food Security and Nutrition: Statistics and Trends, FAO, Cairo, 2021.
GCC Petrochemicals and Chemicals Association, Plastics and Polymer Consumption in the GCC: Trends and Outlook, GPCA, Dubai, 2019.
General Food Security Authority, Saudi Arabia Food Loss and Waste Index: Baseline Assessment, General Food Security Authority, Riyadh, 2020.
Government of Saudi Arabia, Saudi Green Initiative: Roadmap to Net Zero by 2060, Government of Saudi Arabia, Riyadh, 2021b.
Government of Saudi Arabia, Updated Nationally Determined Contribution of the Kingdom of Saudi Arabia under the Paris Agreement, Government of Saudi Arabia, Riyadh, 2021a.
International Energy Agency, CO_2 Emissions from Fuel Combustion Highlights, International Energy Agency, Paris, 2023.
KAPSARC (King Abdullah Petroleum Studies and Research Center), Industrial Energy Use and Decarbonization Pathways in Saudi Arabia: Insights from GCAM-KSA, KAPSARC, Riyadh, 2020.
Lieder, M., and Rashid, A., Towards circular economy implementation: A comprehensive review in context of manufacturing industry, Journal of Cleaner Production, vol. 115, pp. 36–51, 2016.
Ministry of Municipal and Rural Affairs and Housing, Municipal Solid Waste Management in Saudi Arabia: Current Status and Future Directions, Ministry of Municipal and Rural Affairs and Housing, Riyadh, 2020.
Patwa, N., Sivarajah, N., Seetharaman, A., Sarkar, S., Mohamed, N., and Gupta, Y., Towards a circular economy: An emerging economies context, Journal of Business Research, vol. 122, pp. 725–735, 2021.

Biography
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