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Cleaning up cleaning: a pathway to net zero for fast moving consumer goods chemical formulations

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Household cleaning products and packaged chemicals sold by fast moving consumer goods (FMCG) companies contribute significantly to global emissions. Once used, these products largely enter wastewater systems and degrade into carbon-based greenhouse gases (GHGs). Such end-of-life emissions can account for up to two-thirds of the product's total, but are often overlooked in both environmental assessments and policy. Here, we examine the decarbonization of the FMCG chemical formulations sector, motivated by four questions. First, is it preferable to substitute fossil-based feedstock with bio-based feedstock, or to continue with fossil feedstocks but with capture and permanent storage of the corresponding atmospheric carbon dioxide? Second, how large are the current cost differentials between fossil-based and viable bio-based feedstocks? Third, what is the potential for cost reductions among bio-based feedstocks, given technology learning curves? Fourth, what carbon prices would make bio-based feedstocks competitive with their fossil-based alternatives? The paper concludes with a discussion of policy options to enable the competitiveness of bio-based feedstocks with their fossil carbon equivalents, opening up a pathway to net zero for household chemical formulations.

KEYWORDS
chemicals, decarbonization, fast moving consumer goods, industry, policy

1 Introduction

To limit global temperature increases to 1.5 °C, carbon emissions from the chemical sector must reach net zero. This is a significant challenge for an important economic sector, which contributes 4% of global GDP. The sector emits approximately 2.2 billion tons of carbon emissions annually, accounting for approximately 6% of global carbon emissions (Saygin and Gielen, 2021). An estimated 94% of carbon used in chemical formulations is derived from petrochemicals (SystemIQ, University of Tokyo, and Center for Global Commons, 2022). This accounts for approximately 14% of annual oil production and 8% of natural gas production (International Energy Agency, 2018). The International Energy Agency (IEA) projects that as fossil fuel demand for energy production shifts, petrochemicals could represent 55% of all oil demand by 2050 (International Energy Agency, 2021). Without a change in current trends, the cost to decarbonize the chemical sector is estimated to exceed 35% of the industry's total energy and feedstock costs by 2050 (International Energy Agency, 2021).

Within the chemical sector, formulations classed as fast-moving consumer goods (FMCG) pose a particular challenge. These products include household cleaners, personal care items, and consumer-packaged chemicals like paints, varnishes, and sealants. FMCG products account for approximately 10% of chemical sector emissions (Bott, 2023). The carbon within FMCG formulations enters wastewater systems at the product's end of life and degrades into carbon-based greenhouse gases (GHGs). These end-of-life emissions can account for up to two-thirds of the product's total, but are often overlooked in both environmental assessments and policy (Fogliatti et al., 2014). To achieve net-zero alignment, FMCG formulations' feedstocks must be either replaced with sustainable carbon from bio-based sources or emissions must be captured and permanently removed from the atmosphere (European Commission, 2023a,b).

This paper examines four issues around the decarbonization of the FMCG chemical formulations sector. In Section 2, we compare the substitution of fossil-based feedstock with bio-based feedstock with the capture and permanent storage of carbon as decarbonization strategies. We find that bio-based feedstock substitution is a more feasible route. In Section 3, we quantify the cost differential between fossil-based and a range of viable bio-based feedstocks such as bio-based kerosene, naphtha, and ethanol. In Section 4, we explore the potential for cost reductions among bio-based feedstocks through the application of technology learning curves developed in the renewable energy sector. In Section 5, we quantify the range of carbon prices and consider other interventions that would make bio-based feedstocks competitive with their fossil-based alternatives. We conclude in Section 6 with a discussion of policy options to enable the competitiveness of bio-based feedstocks in general, opening up a pathway to net zero for household chemical formulations. This paper focuses on the use of carbon feedstocks for chemical formulations, rather than their use as energy carriers or fuels; therefore, considerations such as combustion performance are outside the scope of our analysis.

FMCG chemicals are an interesting case to examine in the broader context of industrial decarbonization. While other sectors such as plastics or transportation fuels also face a trade-off between bio-based feedstock substitution and carbon removal, in the FMCG sector this takes place in especially difficult circumstances: FMCG formulations are a commodity market, there is a wide variety of consumer choice and sensitivity to consumer sentiment in FMCGs, the sector faces strict regulatory environments, and recycling of carbon is not possible due to the complex nature of end-of-life emissions for formulations. As such, the interventions to decarbonize FMCG formulations are among some of the most difficult in the sector, and may prove a helpful starting point for examining similar complex industrial challenges across the global net zero transition.

2 Options for decarbonization of chemical formulations

We review the literature to compare two options for decarbonizing household chemical formulations: substituting petrochemical feedstocks with bio-based feedstocks, and capture and permanent storage of carbon. We find that bio-based feedstocks are a more feasible option due to the state of technological maturity, and because they better account for "hidden" emissions across the life of a chemical product.

2.1 Carbon capture and permanent storage

Using permanent carbon removal methods to offset the emissions of fossil carbon is theoretically possible, but with challenges. First, cost is a significant barrier. Removal costs today are estimated between USD 200–1,000 per ton, compared to a carbon price of USD 81–94 per ton traded on European and UK markets (Vaughan et al., 2024). While the cost of removals is likely to fall in the future, it is unclear how far and over what timescale due to uncertainty around both demand and technological maturity (Vaughan et al., 2024). The technology for large-scale permanent removal is also not yet developed to industrial scales, and it is unclear whether it will do so on a timeline required for Paris Agreement commitments (Vaughan et al., 2024). Thus, the cost of removing carbon is likely to exceed the "payout" on the carbon market in the foreseeable future. Uncertainty and unfavorable costs thus make carbon storage and permanent capture a risky choice for decarbonizing FMCG formulations.

Second, storage and permanent carbon removal must account for the entire lifecycle of carbon embedded in chemical formulations, which is currently poorly monitored and assessed. For example, a comprehensive understanding of emissions should include often overlooked factors like "hidden" methane leakage from oil and gas extraction (Johnson et al., 2022; Opara and Okere, 2024). Methane leakage is typically underreported and challenging to monitor and validate (Tollefson, 2013), and recent studies have shown that these emissions are often significantly underestimated (Franklin et al., 2022; Schneising et al., 2020). Additionally, carbon removal efforts must account for emissions released when formulations are disposed of in water treatment plants. This is a significant factor, as in some cases, end-of-life emissions can constitute two-thirds of a product's total emissions (Fogliatti et al., 2014). Due to the inconsistent monitoring of these end-of-life emissions, it is difficult to accurately quantify the scale of emissions that a permanent storage process would need to address.

Figure 1 shows the different stages of emissions during formulation production, highlighting the "hidden" emissions in red.

2.2 Substituting fossil-based feedstocks for bio-based feedstocks

The presence of "hidden" and wastewater emissions in formulations necessitates a different approach to achieving net-zero alignment than is used for products like plastics, where recycling and capture are more feasible (Vidal et al., 2024). Bio-based feedstocks offer a compelling alternative. The use of bio-derived chemicals made using carbon from plants gives a reduction in emissions (on a cradle-to-grave basis) of between 39 and 86% compared to fossil feedstocks (Adom et al., 2014). This is because

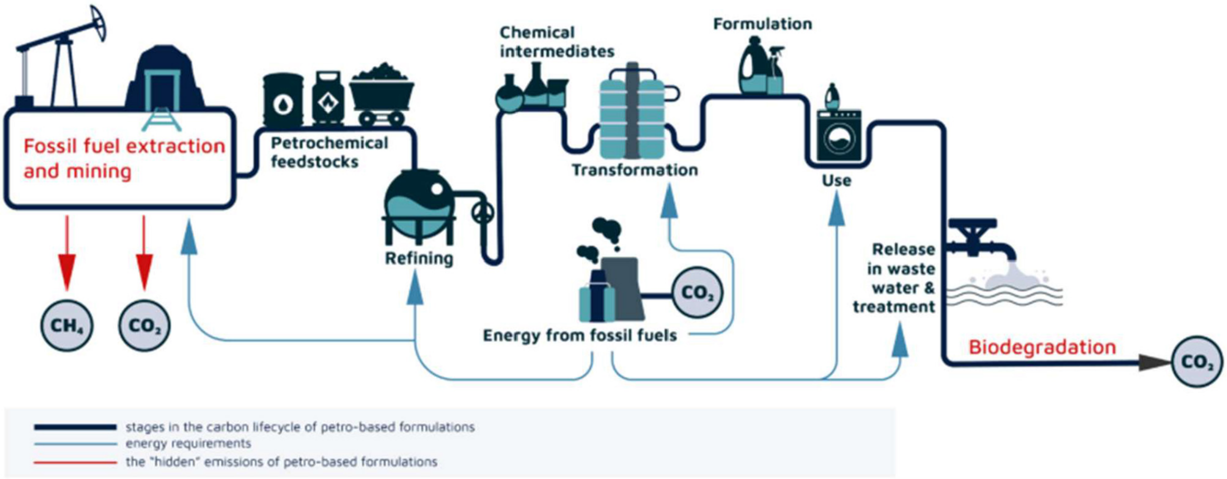

FIGURE 1
Schematic showing emissions related to formulation production using fossil-based carbon feedstocks. "Hidden" emissions are highlighted in red. Source: Collett et al. (2023).

using bio-carbon creates a circular loop: the carbon released from biodegradation of formulations and leaks along the value chain is equivalent to the carbon absorbed from the atmosphere to grow the feedstock crop. As such, the use of bio-based feedstocks figures in "hidden" and leaked emissions that are hard to quantify when using carbon removal and permanent methods. This makes bio-based feedstocks an attractive option for decarbonization.

However, several barriers currently slow the uptake of bio-based feedstock alternatives at a global scale. In particular, it is important to consider non-climate-related environmental impacts of bio-based feedstocks. There are many sources of bio-carbon, including virgin vegetable oils, byproducts and waste materials. Each has different considerations such as emissions, availability, competition, land requirements, cost and crop-to-chemical efficiency. To ensure bio-carbon has lower associated emissions than fossil-carbon, the energy to cultivate the source must be renewable energy, land-use changes must not release naturally stored carbon into the atmosphere (i.e., no deforestation for crop growth), and fertilization requirements in the long-term should be met using sustainable chemicals and practices. There are no clear assessments of the overall land use requirements if all FMCG formulations were to be made using sustainable carbon. However, there will likely be some competition for land use between agricultural land, bio-based feedstock land, and protecting ecosystems for rewilding and protection such as rainforests and wetlands. Unless carefully considered, constraints related to sustainable land use could cause price inflation of bio-carbon supply or trigger regulatory intervention to prohibit use (e.g., as with palm oil).

Taking the case of palm oil, the scale of these issues becomes clear. The production of palm oil, a key source of bio-carbon, often has considerable environmental impacts such as biodiversity loss, deforestation, and unsustainable use of fertilizers. For example, peat drainage in Southeast Asia undertaken largely to clear land for palm oil is estimated to contribute the equivalent of 2% of global fossil fuel CO_2 emissions (Petrenko et al., 2016). While groups like the Roundtable on Sustainable Palm Oil (RSPO) have set standards, at present, only 19% of palm oil is verifiably produced sustainably according to RSPO (Roundtable on Sustainable Palm Oil, 2020). The sustainable production of bio-carbon at scale remains a significant challenge to resolve.

Bio-carbon sources are often classified in different "generations" by the chemical industry. First-generation feedstocks are crops in the food chain, such as corn and sugarcane, and edible oils such as palm and soy. Second-generation feedstocks include non-edible crops such as agricultural waste, wood and used cooking oils. The third-generation category is for algae, including seaweed. The circular carbon cycle for using bio-based feedstocks is shown in Figure 2.

While the technological maturity of bio-based feedstocks is greater than that of carbon removal and permanent storage methods, production is not yet at a sufficient scale to supply the chemicals sector. Maturity is generally correlated to the "generation" of bio-carbon, with first-generation feedstocks like sugarcane more advanced than second- and third-generation feedstocks like wood or algae. Common sources of bio-carbon and intermediate platforms for surfactant feedstocks are summarized in Figure 3. The process maturity level is indicated by the type of line.

To ensure a steady and affordable supply of net-zero aligned carbon for the chemicals industry, it is crucial to scale up the production of bio-based feedstocks. Without sufficient supply, prices could rise, making bio-based feedstocks uncompetitive. A consistent supply is also necessary to prevent competition between sectors for commodities like bio-ethanol or bio-kerosene (sustainable aviation fuel). Forums for sectoral and international coordination have not hitherto focused on the lack of sustainable chemicals for formulations. However, given the broad competition for sustainable feedstocks across various products, international coordination between countries and companies is essential. This coordination should prioritize creating the economies of scale necessary to make sustainable feedstocks cost-competitive for the FMCG and other sectors.

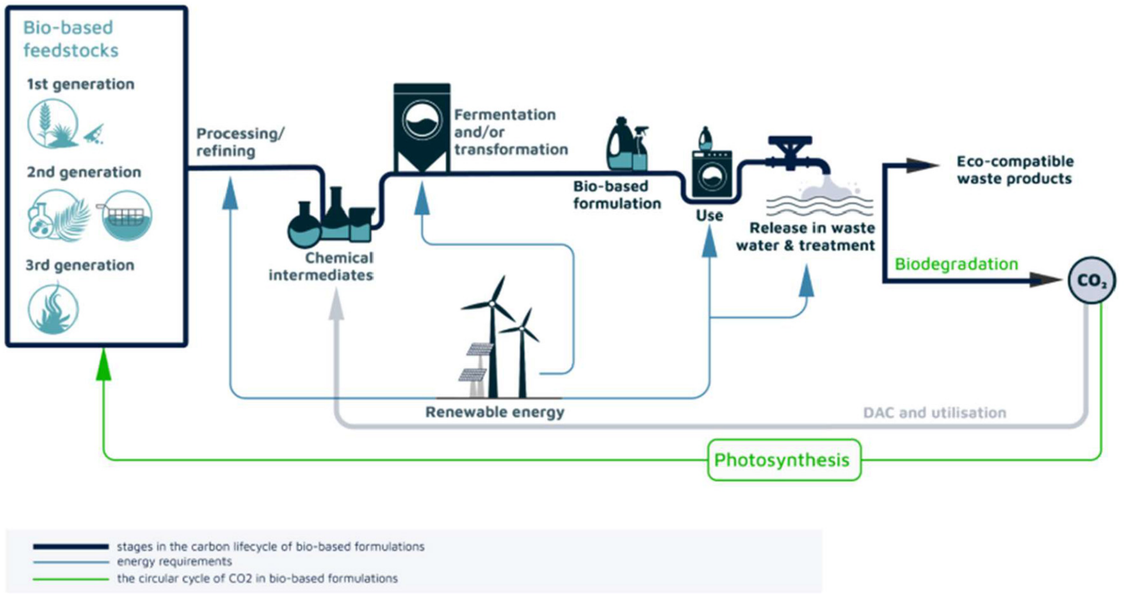

FIGURE 2
Schematic showing emissions related to formulation production using bio-carbon. Provided biodegradation to CO_2 is matched with photosynthetic capture of CO_2 (both in green), the system can be circular. Source: Collett et al. (2023).

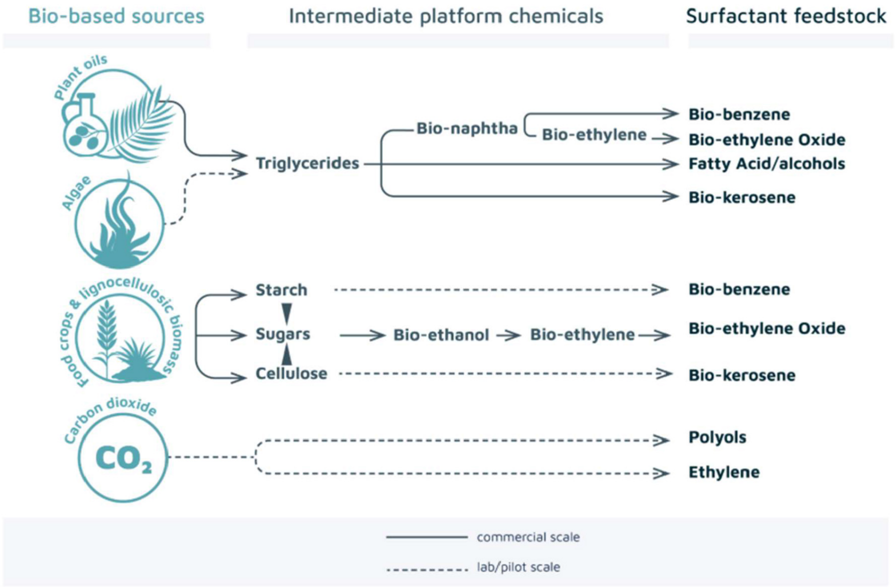

FIGURE 3
Four key sustainable sources of carbon and the platform chemicals they can produce. Process maturity level indicated by the type of line (dashed or solid). Source: Based on Coady et al. (2017) and de Jong et al. (2020).

Bio-based feedstocks have a significant economic advantage: uncoupling the cost of formulations from the cost of oil. Petrochemical feedstocks are subject to volatility in oil and gas prices, influenced by supply shocks from international conflicts or demand shocks like the rapid recovery from the COVID-19 pandemic (Bouazizi et al., 2024; Kelly et al., 2022). As the pathway to net zero progresses, the reduced supply of fossil fuels means the price of oil is likely to be more volatile than today, before it eventually declines as only reserves with the lowest costs of extraction are exploited. The US Energy Information Administration forecasts that under a high price scenario, Brent crude could increase to US$190/bbl by 2050, almost 2.8 times the 2023 price (J.P. Morgan Research, 2025; U.S. Energy Information Administration, 2023). The risk of such a scenario, along with ongoing geopolitical disruptions, provides a strong incentive for industries that depend on petrochemicals to diversify their feedstocks. Incorporating sustainable chemicals can help protect their business models from long-term increases in feedstock costs (Bosch et al., 2017).

In conclusion, the comparative technical maturity of bio-based feedstock production compared to carbon removal, alongside the fact that it accounts for hidden or leaked emissions, makes it a compelling decarbonization pathway. Diversification and resilience against petrochemical price shocks present further advantages. However, non-climate environmental impacts and a scaling up of production processes must be addressed to make bio-based feedstocks a viable decarbonization pathway at scale and at pace.

2.3 Land use constraints and scalability of bio-based feedstocks

A central challenge for the large-scale deployment of bio-based feedstocks is the availability and use of land. Unlike fossil-carbon sources, which are geographically concentrated and energy-dense, bio-carbon production depends on biological growth processes that require land, water, and other ecological resources. This creates direct competition with food production, biodiversity conservation, and other ecosystem services, and imposes constraints on the extent to which bio-based feedstocks can be scaled sustainably (Nabuurs et al., 2022; Searchinger et al., 2018).

These constraints have important implications for the cost dynamics of bio-based feedstocks. Economies of scale are likely to arise in processing technologies, supply chains, and learning-by-doing as production expands (Slade et al., 2014). However, at the level of feedstock production, increasing demand may lead to rising marginal costs as production expands onto less productive, more environmentally sensitive land, or land used for critical food production or other activities affecting lives and livelihoods (Creutzig et al., 2015; Searchinger et al., 2018). This introduces the potential for diseconomies of scale in biomass supply, particularly where sustainability or human development and welfare constraints limit the availability of suitable land.

Taken together, the current evidence does not suggest that land use constraints render the transition to bio-based feedstocks infeasible, but it does indicate that unconstrained substitution of fossil-carbon with bio-carbon at a global scale is unlikely (IEA, 2024). Instead, the scalability of bio-based feedstocks will depend on how effectively these constraints are managed across regions and sectors (Daioglou et al., 2019). This includes improving land-use efficiency, prioritizing high-value applications, and avoiding adverse environmental impacts such as deforestation or biodiversity loss, and balancing feedstock growth against agricultural requirements (Creutzig et al., 2015; Tilman et al., 2011).

A range of strategies can help mitigate land constraints and support sustainable scaling. These include increasing the use of waste-derived and residue-based feedstocks, expanding second- and third-generation biomass sources such as lignocellulosic materials and algae, and utilizing crops that can be grown on marginal land, including (CAM Crassulacean Acid Metabolism) plants such as agave and certain cacti, use a water-efficient photosynthetic pathway that allows them to grow on arid or marginal land, thereby helping to overcome land-use limitations (IEA, 2024; Nabuurs et al., 2022; Creutzig et al., 2018; Collett et al., 2021a,b). In addition, improved ecosystem mapping and land-use planning can help identify areas where biomass production can be expanded with minimal environmental trade-offs (Nabuurs et al., 2022), while coordination across sectors can reduce inefficient competition for limited resources (IEA, 2024).

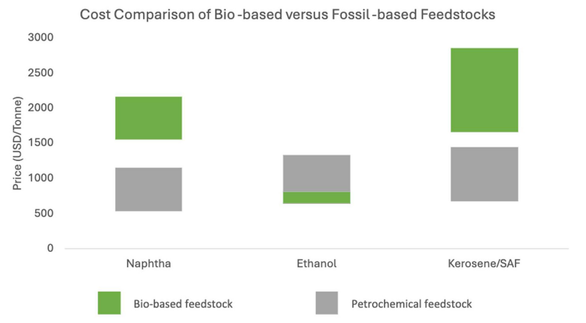

FIGURE 4
Cost differential between commonly used petrochemical and bio-based feedstocks for chemical formulations. Source: Businessanalytiq (2025b,c,a,d), Quantum Commodity Intelligence (2025c,b,a), and Trading Economics (2025).

Overall, land use constraints should be understood as an important but manageable factor that shapes where and how bio-based feedstocks can scale, rather than a fundamental barrier to their deployment. Addressing these constraints will be critical to ensuring that the transition to sustainable carbon sources is both environmentally and economically viable.

3 Quantifying cost differentials between fossil-based and bio-based feedstocks for chemical formulations

Bio-based feedstocks are on average more expensive than their fossil-based equivalents today (Wellenreuther et al., 2022). The price differences vary significantly by chemical type. For naphtha, premiums for bio-based chemicals range from 34 to 88%. Kerosene feedstocks show similar high premiums for bio-based chemicals, from 15 to 98%; however, bioethanol is competitively priced compared to its fossil equivalent, at around $640 per ton (see Figure 4).

Four primary reasons explain why fossil-based formulation has historically been inexpensive. First, fossil-based carbon comes from petrochemicals, which are a byproduct of oil and gas extraction that could otherwise be considered waste. Capitalizing on a byproduct of a global energy system reliant on petrochemicals has made fossil-based formulations extremely cost-competitive. Second, the petrochemical industry is mature, optimized and efficient, with refinery processes having been established in the 1850s and reaching significant economies of scale. Additionally, all refined chemical products have a market, resulting in very little waste of petrochemical feedstocks. Third, fossil fuel extraction still receives significant subsidies from governments to incentivize cheap energy production (Coady et al., 2017), reducing the cost of petrochemicals. Fourth, environmental externalities from fossil carbon are not priced into the cost of carbon used for plastics or formulations. These "hidden" emissions make fossil-derived carbon appear to be the cheapest source for formulations and plastics.

Reducing the cost of feedstocks is a significant consideration for the chemicals industry as surfactants can make up as much as 60%—70% of procurement costs (PW Consulting Chemical Energy Research Center, 2025). As a result, achieving cost-competitiveness for bio-based feedstocks is essential for their uptake at scale. It is important to note that the processing of the feedstock into a surfactant is the technically very similar regardless of whether it is bio-based or petrochemical-based, and can be considered equivalent in cost (Bartling et al., 2021; International Renewable Energy Agency, 2013). However, bio-based feedstocks whose processes are powered by fossil fuel energy may also be affected by fossil prices.

4 Potential for bio-based feedstock cost reductions

Bio-based feedstocks are an emerging market, and their learning rate and corresponding price trajectories are unclear due to insufficient data on historical price points. However, lessons about potential cost reductions over time can be taken from other technologies. This can allow us to infer the point at which bio-based feedstocks may become cost-competitive in the future.

If bio-based feedstocks are to follow a similar learning rate as advanced biofuels, production costs may fall by between 5 and 27% in the next 10–15 years (IEA Bioenergy, 2020). Reducing capital costs of production infrastructure can contribute to additional reductions of between 5 and 16% (IEA Bioenergy, 2020). These figures are reasonable when benchmarked against the learning rates of other green technologies such as renewable energy generation (10% p.a.), lithium-ion batteries (12% p.a.), and transistors and optical fibers (40%—50% p.a.) (Way et al., 2020). A variety of policy mechanisms enabled these high learning rates, including carbon taxes, subsidies and portfolio standards (Lam and Mercure, 2021; Ryan et al., 2019). Applying similar interventions to bio-based formulations is likely to enable significant learning rates.

Modeling learning rates of 5%, 10%, 15%, and 20% from today's prices for key bio-based feedstocks shows that a sectoral transformation toward net-zero aligned feedstocks for the chemical industry appears likely even at moderate rates (Figure 5).

Figure 5 shows the cumulative demand for bio-based feedstocks by 2050 with a dashed vertical line, while the current price range for fossil-carbon alternatives is represented by the horizontal gray bar. For this analysis, the current price of fossil-based feedstocks is used as a conservative baseline due to the uncertainty of future costs, which could rise or fall toward 2050. The price of crude oil, for example, could fall if oil demand declines markedly. But oil prices could also increase by 2.5 times by 2050 (U.S. Energy Information Administration, 2023) given depletion of existing fields, which would directly impact the cost of petrochemical feedstocks. Such an increase would accelerate the point at which bio-based feedstocks reach price parity with their fossil-based counterparts.

This analysis indicates that bioethanol is already cost-competitive with its fossil counterpart, and under all learning rate scenarios out-competes fossil alternatives by 2050. Bio-naptha and bio-kerosene require steeper learning curves of 15% to 20% to reach price competitiveness by 2050. These higher learning rates would require significant political and stakeholder support to achieve a timely transition. However, given the relative shortage of bio-naphtha and bio-kerosene relative to demand (IEA, 2022b, 2023), it is not unreasonable to expect significant learning rates as production scales.

Reaching learning rates of 15% to 20% is not guaranteed if the status quo of investment and demand continues. Accelerating learning rates requires an effective, sustained portfolio of interventions. The precise relationship between interventions and a certain learning rate is difficult to quantify, beyond the general trend of increasing interventions likely increasing the learning rate. In Section 5, we discuss a range of interventions and how they could lead to learning rate accelerations, with a particular focus on carbon pricing. In any case, these results emphasize the importance of policy measures to level the playing field between bio-based and fossil-based feedstocks, especially for bio-naphtha and bio-kerosene.

5 Interventions for bio-based feedstock cost competitiveness

In this section, we discuss a selection of interventions that could accelerate learning rates and improve the cost competitiveness of bio-based chemicals relative to fossil-sourced petrochemical feedstocks. These interventions are grouped into six areas: increasing the cost of fossil carbon, making bio-carbon more competitive, funding innovation, demand pull, supply push, and capacity building.

Hepburn et al. (2020) highlight the value of taking a portfolio approach, with policymakers selecting a set of contextually suitable interventions. We call for the development of a sustainable carbon strategy using a variety of levers, outlined comprehensively in Figure 6 below.

5.1 Increasing the cost of fossil carbon

Increasing the cost of fossil carbon sends a strong political and economic signal to reduce its use in formulations. Economists widely support carbon pricing as a mechanism to alter relative prices in favor of bio-based alternatives, leading to an adjustment in behavior by firms and consumers, and providing incentives for investments in low-carbon technologies (Carattini et al., 2018). In this section, we present calculations for setting a price of carbon at which bio-based feedstocks would become cost-competitive. We also explore the possibility of combining this with a carbon-border adjustment mechanism, and considerations of "just" pricing and public acceptability.

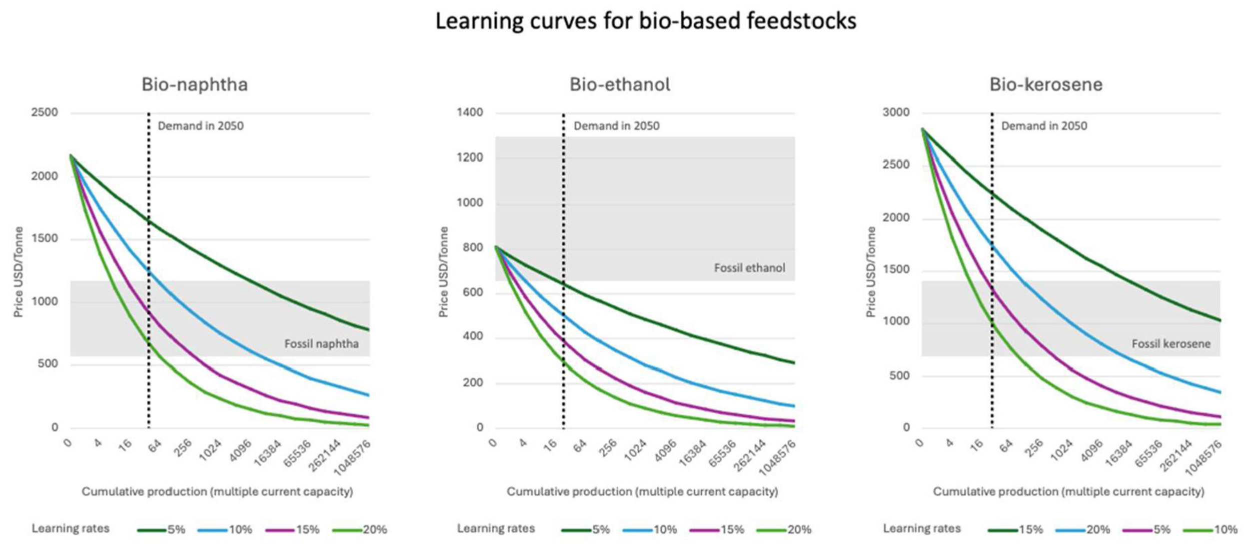

FIGURE 5
Learning curves for bio-naphtha, bio-ethanol, and bio-kerosene (from left to right) with 5%, 10%, 15%, and 20% learning rates. Sources: Businessanalytiq (2025b,c,a,d), ChemAnalyst (2025b,c,a), Quantum Commodity Intelligence (2025b,c,a), and Trading Economics (2025). Fossil price ranges shown do not incorporate carbon prices.

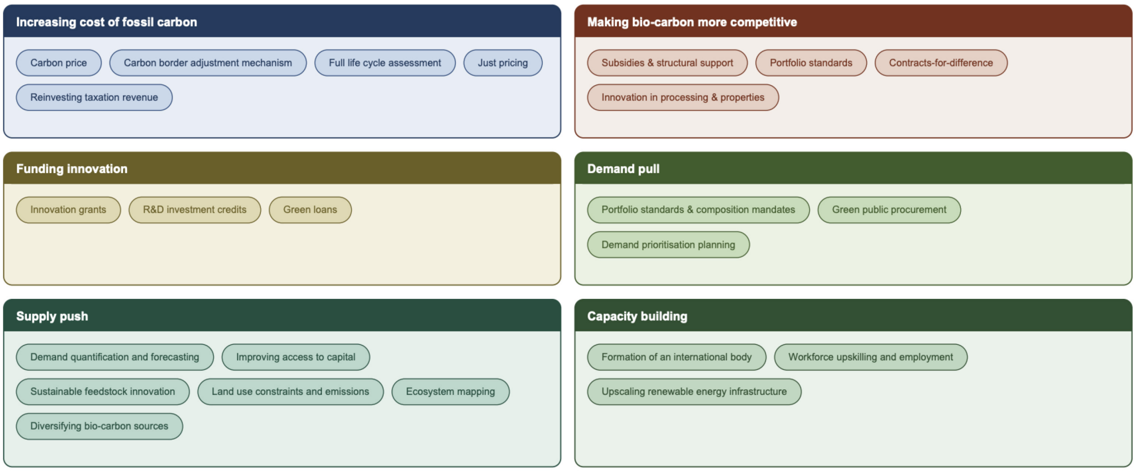

FIGURE 6
Portfolio of policy and stakeholder interventions to support sustainable carbon in chemical formulations. Source: Collett et al. (2023).

5.1.1 Carbon price

While 113 carbon price instruments have been implemented across 55 jurisdictions worldwide, covering about 28% of global greenhouse gas (GHG) emissions in 2022 (Figure 7) (World Bank, 2025), these initiatives predominantly apply to carbon from energy generation rather than industrial uses like those from the chemicals sector (World Bank, 2025). In fact, the chemicals sector has historically received free allocations to pollute in key jurisdictions like the European Union, as large parts of the bulk organic chemicals sector are exempt from the European Emissions Trading Scheme (EU-ETS) (European Commission, 2011). Exceptions or generous allowances like these exceptions mean that coverage is not as comprehensive or effective at bringing down emissions as it is in other sectors (European Commission, 2025; Ruggiero, 2021). For example, between 2019 and 2020, the European Union chemicals sector reduced emissions by just 1.9%, far below other industrial counterparts such as iron and steel, whose emissions reduced by 11.5% and 8%, respectively (European Environmental Agency, 2022). The ineffectiveness of the current EU-ETS application to the chemicals industry suggests that the carbon prices for the chemicals sector ought to be re-evaluated.

We calculate a “tipping point” theoretical carbon price at which it becomes optimal to switch from fossil-based to bio-based feedstocks. Previous estimates of a carbon price for bio-chemicals were made by Saygin and Gielen (2021) at US\$100–400/tCO_2eq. This is considerably higher than typical carbon prices, which range from US\$0.1–158.8/tCO_2eq in 2025 (World Bank, 2025).

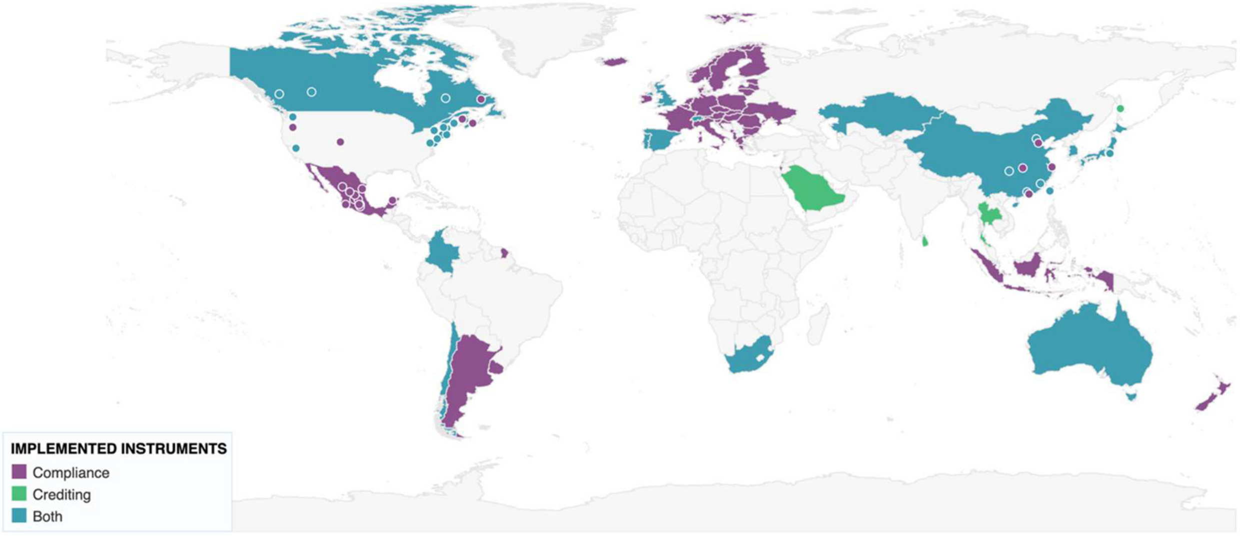

FIGURE 7
Map showing jurisdictions with implemented carbon pricing mechanisms in 2025. Source: World Bank (2025).

We use a cradle-to-grave lifecycle benchmark of emissions developed by Dray et al. (2022) to calculate a "tipping point" carbon price for bio-kerosene to become competitive with fossil kerosene. Table 1 presents the calculations for the theoretical carbon price per ton for bio-kerosene that would, all else being equal, equalize the post-tax price of fossil and bio-based feedstocks.

The calculations in Table 1 suggest a theoretical tipping point carbon price between US$259–840/t$CO_2$eq to make bio-benzene cost competitive with fossil-carbon benzene feedstocks. These figures should be taken as indicative, as data on feedstock costs is limited and the whole-of-lifecycle assessment of emissions by Dray et al. acknowledges gaps in analysis. With improved cost data and lifecycle emissions measurements, the carbon price is likely to reflect a more accurate figure.

A carbon price of US$259–840/t$CO_2$eq is significantly higher than those on global markets, which ranged from US$0.1 to US$158.8 in mid-2025. It also exceeds target global average price levels of US$50–100/t$CO_2$eq by 2030, calculated as appropriate for economic decarbonization incentives by a group of leading environmental economists (Stern et al., 2022).

Given that the formulations sector tends to function as a commodities market that internalizes costs rather than passing them on to consumers, implementing a uniquely high carbon price for the chemicals industry, in line with the theoretical price, is unlikely to be a feasible short-term intervention. Such a high price would adversely affect the sector's competitiveness in implementing geographies, to the point of encouraging sourcing of feedstocks from non-implementing jurisdictions (Kearney, 2022; Statista, 2025). However, a carbon price at the lower end of the suggested range, or even lower, could create a robust political signal that the chemicals industry is not exempt from net-zero aligned transformation. The trend of cost internalization can also be counterbalanced by structural support measures for research and development (R&D) and innovation in net-zero aligned formulations (see Section 4 above). An initially lower carbon price could also be increased over time on a set schedule, a policy approach that has been linked to higher public and industry support (Burke, 2019).

TABLE 1 Theoretical carbon price for kerosene using cradle-to-grave lifecycle emissions.

Kerosene	Fossil	Bio-based	Difference
Price (US$/ton)	242 Range: 670–1,440	1,282 Range: 1,653–2,853	1,040 Range: 983–2,183
Emissions (Dray et al., 2022) (tCO_2eq/ton)	5.2	2 Range: 1.4–2.6	3.2 Range: 2.6–3.8
		Carbon price: (US$/t$CO_2$eq)	325 Range: 259–840

5.1.2 Carbon border adjustment mechanism

A carbon border adjustment mechanism (CBAM) supports a robust approach to carbon pricing by addressing the carbon entering a specific area via imports (Helm et al., 2012). This prevents "outsourcing" of carbon emissions to producers outside a particular jurisdiction. CBAMs can take three forms: (i) border taxes (as tariffs on imports and, less commonly, rebates on exports); (ii) mandatory emissions allowances purchased by importers; and (iii) embedded carbon product standards. CBAMs are a popular tool for improving the competitiveness of industries within the agreement relative to outside producers, with revenue raised providing income for investment into decarbonization efforts like R&D subsidies (Adams et al., 2022). A CBAM can be a key component of a policy package that is favorable to industry.

However, CBAMs face significant implementation challenges. For multinational supply chains, a large number of economies (e.g., those representing the majority of imported goods) must be included to be effective. A comprehensive, universally verifiable system for carbon accounting and measurement is also required, along with compatibility with international trade regulations like those of the World Trade Organization (WTO). This is challenging as the chemicals industry is currently excluded from the European Union's CBAM due to uncertainty about the embedded emissions of these goods upon import (European Commission, 2021). The European Commission's CBAM proposal explicitly notes the need for more data and analysis of this sector before it can be included. This highlights the need for investment in the full lifecycle analysis of key chemical feedstocks and products.

5.1.3 Full lifecycle analysis

Lifecycle calculations are in the very early stages of being incorporated into carbon pricing (World Bank, 2022). Given the end-of-life emissions from formulations, a cradle-to-grave lifecycle emissions approach is required for the chemicals sector (Intergovernmental Panel on Climate Change, 2023). Without this approach, a significant share of FMCG formulations emissions would remain unaccounted for, and any attempt to quantify associated externalities via a carbon price would be inaccurate. Although organizations like the World Business Council on Sustainable Development (WBCSD) are working to standardize lifecycle analysis methodologies (World Business Council For Sustainable Development Chemicals, 2014), widely agreed-upon and compatible methods have yet to be established globally.

5.1.4 Just pricing

Distributional effects must be carefully considered in designing a carbon price or CBAM on FMCG formulations. The products subject to such a scheme are essential goods with relatively inelastic demand, and consumers are unlikely to be able to substitute for cheaper alternatives during cost-of-living pinches. This is particularly relevant for low-income households: for example, in the UK, the lowest income quintile spends 3.3% of their total expenditure on FMCG formulation products (Office for National Statistics, 2021). Price cap regimes which limit the pass-through of higher costs to consumers, rebates, or policies which require the taxation cost to be internalized by the manufacturers could mitigate distributional impacts (Carattini et al., 2019).

5.1.5 Reinvesting taxation revenue

The public acceptability of pricing schemes can be improved by hypothecating revenue raised to support sustainability investments, or in rebates to support low-income consumers (Carattini et al., 2018). Some groups advocate for "climate dividends," which are per-capita pay-outs to citizens from the carbon tax collected (Carattini et al., 2018). This is already implemented in Switzerland through a tax and rebate on heating fuel, and in Canada's domestic carbon tax scheme (Burke, 2019; Mildenberger et al., 2022).

In both theory and practice, carbon prices should not necessarily be equal across countries (Hepburn et al., 2020). This is due to equity considerations, economic structures and different elasticities in low-income vs. high-income countries across products (Hepburn et al., 2020; Stern et al., 2022; Stiglitz, 2019). For example, lower capital and labor costs in low-income countries can result in different production costs for formulations, meaning that a local carbon price may be most effective at driving decarbonization in this jurisdiction compared to a global one. Furthermore, a higher price elasticity of emissions in low-income countries means that a relatively lower carbon price can have a more significant impact on emission reductions (Stern et al., 2022; Stiglitz, 2019).

5.2 Making bio-carbon more competitive

In addition to carbon taxation and carbon border adjustment mechanisms (CBAMs), other interventions such as contracts for difference (CfDs), subsidies, and structural support can also increase the competitiveness of bio-carbon by impacting feedstock costs. Furthermore, mid-term innovations in processing can lead to permanent cost reductions independent of financial support.

5.2.1 Subsidies and structural support measures

Subsidies such as feed-in-tariffs for renewable energy and capital subsidies for clean technologies like heat pumps and electric vehicles are extensively used to accelerate net-zero transitions of key sectors, and to incentivize private investment. Despite their comparatively smaller size compared to fossil fuel subsidies, renewable subsidies in the energy sector are still significant figures, standing at $166bn in 2017 (Taylor, 2020). Subsidies have often come under political scrutiny, with policies criticized for creating market distortions or leaving governments exposed to long-term expenditure due to the uncertainty of learning curve trajectories, or other exogenous factors such as the exposure of the subsidy mechanism to external shocks. For instance, the energy price spikes of 2022 (triggered by the Ukraine war) fed through to all electricity prices that were set by the cost of fossil gas at the margin, increasing the costs to both consumers and the exchequer (Evans, 2022). Alongside directly subsidizing renewable energy, an alternative reduction in subsidies to fossil fuels should be considered (IEA, 2025; International Monetary Fund, 2025).

5.2.2 Portfolio standards

Portfolio standards are a market-based instrument used to scale up emerging technologies. For example, the UK Renewable Obligation introduced in 2002 was designed to support electricity suppliers to procure a proportion of their supplies from renewable sources (Foxon et al., 2005). Renewable obligation certificates (ROC) were issued free of charge to electricity generators by Ofgem (the administrator of the scheme). Certificates could be sold at a premium to traders or suppliers who were required to meet the Obligation, or instead make a fixed payment into a cash payment fund in lieu of each ROC. Cash payments were recycled back to suppliers who met their obligation with ROCs, incentivizing certificate holds to meet their commitments. However, the cost of the ROC was ultimately passed on to consumers through their electricity bills, which prompted a shift to other support mechanisms.

From 2010 to 2019, the UK moved to Feed-in Tariffs (FiTs), under which accredited electricity generators received support for 10 to 25 years, depending on their technology type and capacity when their installation was commissioned. This support also depended on whether the project was previously accredited under contracts for difference.

5.2.3 Contracts-for-difference

Contracts for difference (CfDs) are policy mechanisms that have been successfully used to scale up novel clean energy-generation technologies like solar and wind, which are now the cheapest sources of new electricity generation globally (Way et al., 2022; Evans, 2022). By extension, sectors which use these technologies as inputs have also undergone rapid cost declines. Successful examples include electric vehicles in the UK, which are now cheaper to run than petrol or diesel cars (Office for Zero Emission Vehicles, 2022).

A CfD mitigates the market risks faced by suppliers of a new, high-cost commodity by paying the supplier the difference between a predetermined reference price reflecting the old technology (for example, a fossil carbon-based feedstock) and a "strike price" set at the value required for the new technology to be viable. The strike price can be determined administratively (for example, in its first renewable CfD round in 2014, the UK government set the strike price), or through competitive reverse-auctions. The counterparty to a CfD is usually a public sector agency or enterprise (in the UK renewable CfD auctions, for example, it is the Low Carbon Contracts Company). CfDs are now being considered in the decarbonization of other sectors, such as maritime shipping (Clark et al., 2021).

The significant cost difference between zero-emission chemical production technologies and their more polluting alternatives on the global market could be bridged through several CfD-based options. One such option is a carbon CfD, where a body like the EU would subsidize producers by covering the cost difference between zero-carbon and more polluting technologies (European Commission, 2023a,b). Research on the UK's CfD scheme for renewables suggests its success was partly due to the preceding policy landscape. The CfD was introduced as a replacement for the Renewable Obligation, which had already established an emerging renewables industry (Clark et al., 2021). This meant that strike and market prices could be benchmarked against existing data, facilitating a smoother transition.

5.2.4 Innovation in processing and properties

In the short term, the direct replacement of fossil-derived formulations with bio-based "drop-ins" is a likely strategy, as this approach utilizes existing refinery infrastructure to reduce additional capital expenditures. Working on innovative new approaches for processing plant matter can significantly reduce the cost of these bio-based drop-ins. For instance, investigating catalysts such as bacteria and enzymes with high activity and selectivity could lead to higher biomass-to-chemical yields (Hayes, 2012). Additionally, improving product separation technology and maintaining a high oxygen-to-carbon atomic ratio in the final product can also improve yields (Huang et al., 2021).

In the mid- to long term, the development of new bio-based formulations for the fast-moving consumer goods (FMCG) sector could offer several advantages. These new formulations could better utilize alternative biomass carbon sources, thereby reducing land use constraints and resource competition. They could also be designed to have superior properties and lower environmental impacts. Critically, the end-of-life decomposition of these new products could be optimized, and standards could be established to mandate biocompatible waste streams.

5.3 Funding innovation

5.3.1 Innovation grants

Government support for early-stage R&D can take the form of innovation funds, such as those created by Innovate UK. These public grants can support riskier, early-stage ventures which have significant potential but are not yet market-ready and thus may not attract sufficient private investment. These grants can be used to direct private investment and ensure positive environmental outcomes while advancing bio-feedstock knowledge. In an example from the plastics sector, the UKRI "Smart Sustainable Plastic Packaging" supports a portfolio of more than 70 funded projects in sustainable plastics research, including investigations into which feedstocks should be grown where for optimal multi-criteria outcomes, with a total budget of £60m over 6 years (UK Research Innovation, 2019).

5.3.2 R&D investment credits

R&D investment credits toward tax relief can be introduced to incentivize private investment. For example, the US Research and Experimentation Tax Credit is a federal benefit that provides companies across a variety of industries dollar-for-dollar cash savings for performing activities related to the development, design or improvement of products, processes, formulas, or software (GovGrant, 2023). If this type of policy were implemented alongside a fossil-carbon taxation regime to incentivize more sustainable feedstocks, it must be designed to prevent carbon leakage. This means that firms that continue to rely on fossil-based feedstocks should not be able to avoid the carbon tax, as this would undermine its effectiveness.

5.3.3 Green loans

To help scale existing ventures, green or national investment banks, such as the Connecticut Green Bank in the U.S. and KfW in Germany, have been investing to scale up companies operating in novel industries (KfW, 2022; Muro and Saha, 2011). These banks leverage private capital by helping companies overcome upfront costs, asymmetric information, and technology costs, thereby enabling new sustainable chemicals to gain market traction and reach new customers.

5.4 Demand pull: encouraging a shift in feedstock demand

An increase in demand for bio-based formulations can be incentivized through standards and regulations, as well as utilizing public procurement and net-zero aligned demand prioritization and planning.

5.4.1 Portfolio standards and composition mandates

By setting clear and achievable targets well in advance, regulators can incentivize the integration of sustainable bio-feedstocks. For instance, renewable portfolio standards (RPS) in the United States have been identified as one of the most effective policies for increasing solar energy adoption (Ryan et al., 2019). This approach signals to suppliers that there will be future demand, thereby de-risking investments in scaling up supply. This type of regulatory signaling has proven effective in the current transition to electric vehicles (EVs), as it provides a predictable transition period for the industry to adjust (Lam and Mercure, 2021).

5.4.2 Green public procurement

Green public procurement (GPP) can help to create stable demand, especially if coordinated across multiple governments (Oxford Smith School Swedish Energy Agency, 2023). Through GPP policies, public entities can steer markets in a sustainable direction by prioritizing environmentally and socially responsible purchases. Public procurement is a significant market force, accounting for an average of 10%–20% of GDP in OECD countries and up to 30% in developing nations (Khorana et al., 2024).

In addition to reducing environmental impacts through procurement choices, GPP programs drive innovative sustainable directions for bio-feedstock markets by identifying future priorities, sharing best practices on bio-based procurement, and increasing local innovation capacity where they are used (Orsatti et al., 2020). This can accelerate market demand for bio-based products at both regional and national levels. To effectively engage the bio-feedstock market and promote demand in end-use industries, public bodies should establish specific strategies for different feedstock chemicals. Coordinating public procurement efforts with R&D support for biotechnologies can effectively promote the development and market deployment of sustainable feedstocks.

5.4.3 Demand prioritization and planning

The prospect of the chemical sector becoming largely bio-based remains challenging, given: (i) the limited availability of sustainable primary biomass; (ii) competition for biomass resources from other sectors such as energy and transport; and (iii) the sheer scale of demand if the entire sector is to be decarbonized. Increased pressure on biomass demand therefore requires careful assessment of trade-offs by adopting the biomass-use prioritization principle on the national or regional level. The "cascading" principle for biomass is proposed in RED III (the revised version of the EU Renewable Energy Directive), which aims to ensure that biomass is used first where it has the highest economic added value and the lowest environmental impact (European Commission, 2023a,b). This requires sectoral coordination both by policymakers and among industries, who require guarantees of stable long-term supply to de-risk switching demand to bio-based carbon.

The formulations sector is not the only sector looking to reduce its greenhouse gas emissions. However, instead of necessarily creating competition for a limited supply, "joint transitions" of several sectors in tandem may have net positive effects. For example, aviation is under increasing pressure to find sustainable biofuels to meet public scrutiny and net-zero pledges. Forecasts predict that the demand for kerosene will grow at between 2.4 and 4.1% per year, which translates to a doubling or tripling of the market by 2050 (Dray et al., 2022). Bio-kerosene is substitutable for fossil-kerosene as a drop-in, meaning aviation is one of the largest potential markets for bio-based chemicals. In a high-demand scenario for bio-kerosene, studies have shown that the market will be capable of producing more than double the quantity required by the aviation sector in 2050 (Dray et al., 2022; Staples et al., 2018). Others show that under lower-demand scenarios where the aviation sector uses a variety of decarbonization methods aside from sustainable aviation fuel, aviation can still drive the development of bio-kerosene to the point where over two-thirds of global use cases in 2050 come from other sectors (World Economic Forum McKinsey Company, 2020). As such, potential "joint transition" benefits should be assessed and considered by policymakers as part of a sustainable carbon strategy for industry as a whole.

5.5 Supply push: sustainably scaling up supply

A sufficient supply of bio-carbon is required to meet demand and provide stable long-term horizons for investment and decarbonization in the chemicals sector. It is critical to accurately quantify and forecast demand across sectors, especially in areas of potential competition for feedstocks. Governments can assist the supply-side of bio-carbon by improving access to capital, introducing sustainable feedstock certifications, and encouraging research into carbon sources, focusing on overcoming land use constraints and diversifying carbon sources.

5.5.1 Demand quantification and forecasting

Policy should encourage the scale-up of bio-based feedstock supply based on accurate forecasting. This includes carefully considering the knock-on effects of limiting supply options for the bio-fuels industry, such as the European Union's decision to phase out palm oil for bio-fuel production and capping crop-based fuels to 7% by 2030 (European Commission, 2018). If supply limitations are necessary to achieve sustainable products, public funding could be directed to advance the state of knowledge of alternative supply options via process R&D or investigating scalable and sustainable crop and land use strategies (Collett et al., 2021a,b). Robust forecasting and resulting planning require policymakers to have a good awareness of supply chain competition and constraints and to adjust strategies as a result.

5.5.2 Improving access to capital

Governments can facilitate optimal supply through financial and regulatory incentives that balance a reduction in financial risks and costs for processing innovative sustainable feedstock against an increase in returns from producing such feedstocks. One strategy to facilitate efficient production at scale is to support integrated biorefineries with the process flexibility to co-produce different bio-based products, such as bio-based chemicals alongside biofuels. This reduces production costs and scales supply by unlocking process efficiencies and reducing financial risks for innovators of sustainable bio feedstock: the entirety of production and profitability is not based on a single novel product but balanced across a range of products.

Financial tools can assist in the development of new refineries as well as the expansion of existing infrastructure. These methods of accessing capital include public co-financing for pilot/demonstration plants to overcome high upfront capital barriers and de-risk further developments through proof of concept, and green bonds that fund capital expenses and improve the financial stability of early investments.

5.5.3 Sustainable feedstock certification

The establishment of robust land use, sustainability, and process practices via standards or codes can ensure a more equitable distribution of environmental burdens. For example, the European Union restricted the importation of commodities like soy, beef, and palm oil grown on deforested land (Zhunusova et al., 2022). This regulation mandates the traceability of product origins to a certain location, thereby incentivizing producers to meet EU standards to access its markets. In a different model voluntary industry standards, like those of the Roundtable on Sustainable Palm Oil (RSPO), aim to improve farming practices through transparency and education (Roundtable on Sustainable Palm Oil, 2020).

For sustainable feedstocks, certification must account for both land use impacts and energy-related emissions from production. Research in this area focuses on understanding land use constraints and ecosystem impacts, while also identifying and developing a more diverse portfolio of carbon sources. These include waste-derived feedstocks (such as agricultural residues, forestry by-products, and municipal waste), non-food biomass grown on marginal land, and novel sources such as algae and engineered biological systems. These diversified carbon sources are often classified in terms of first-, second-, and third-generation feedstocks (e.g., first-generation: sugarcane, corn, palm oil; second-generation: lignocellulosic biomass such as agricultural residues, wood, and used cooking oil; third-generation: algae and seaweed).

5.5.4 Land use constraints and emissions

How land is used significantly impacts greenhouse gas emissions (UNFCCC, 2025). Sustainable land and ocean management can create valuable carbon sinks, while poor management, such as deforestation for agriculture, releases substantial emissions.

Although palm oil is currently the most effective bio-carbon source for the formulations industry, its use faces significant sustainability and land use challenges (Meijaard et al., 2020). The future availability of biomass is uncertain due to current land use patterns, climate change, and biodiversity loss. To enable a confident transition from fossil-based carbon, research is needed to accurately quantify biomass availability for the formulations and broader chemical industries.

Figure 8 presents an overview of where biomass is currently distributed in vegetation globally, indicating potential hubs of purpose-grown production (European Space Agency, 2019). However, the capacity of states and regions to use waste as feedstock products for surfactants should not be overlooked, as this can provide a significant share of feedstocks or energy sources for surfactant production (Black and Richter, 2010).

The biomass strategy of states (as well as sectoral practices) must carefully consider the competing uses of land that can be used to produce biomass, such as food production, conservation, biodiversity protection or living space for humans. These considerations should particularly consider developing economies where biomass makes up a large share of the energy mix, and a diversion of resources toward bio-based feedstock production could cause significant harm. For example, fuel wood provides almost 90% of the energy in rural areas of Kenya, and biomass accounts for 97% of total primary energy supply in Malawi (Black and Richter, 2010). It is therefore essential to identify the most feasible and efficient portfolio of biomass tailored to specific states and regions (Sertolli et al., 2022).

5.5.5 Ecosystem mapping

Ecosystem mapping will be critical for assessing the sustainability of alternative feedstocks and selecting appropriate land for their cultivation, for example, by enabling detailed lifecycle analyses. For instance, unlike palm, crops like rapeseed and

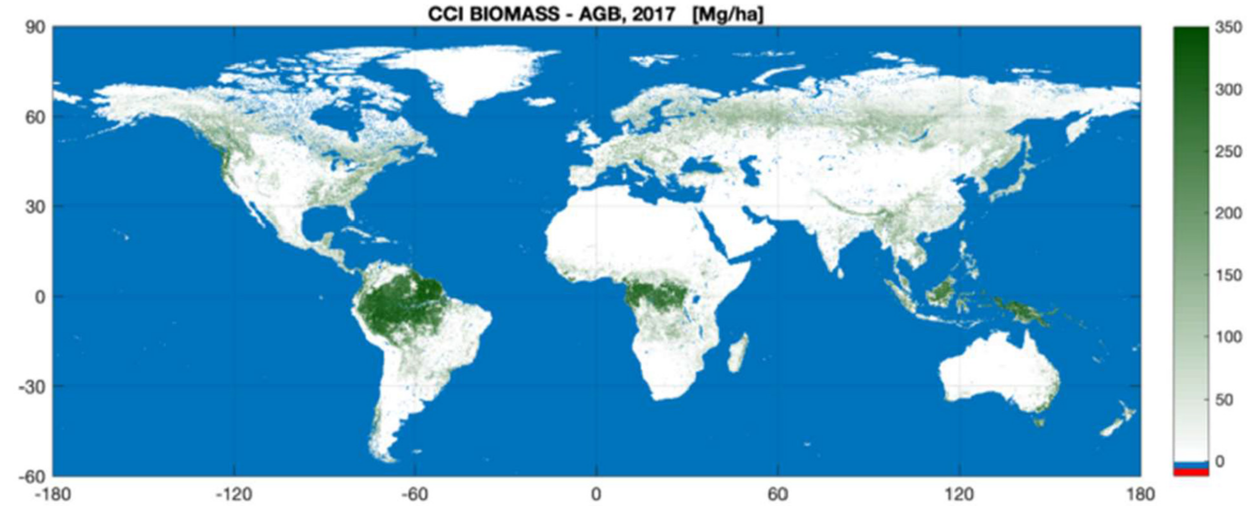

FIGURE 8
Overview of global biomass distribution. Source: European Space Agency (2019).

sunflower can be grown across large areas of central and southern Europe and western Asia. Ecosystem mapping can evaluate the environmental and biodiversity impacts of this cultivation, prioritize low-impact sites like brownfield land, and assess risks such as flooding. This allows for the development of specific land-management practices that maximize crop yield while ensuring proper waste management and the optimal use of pesticides and fertilizers to maintain soil health, minimize emissions, and protect local water systems.

Brazil provides a case study of how ecosystem monitoring and policy can support sustainable land use. Conditional cash-transfer programs like Bolsa Floresta and Bolsa Verde incentivize rural families to conserve forests, while the National Institute for Space Research's satellite imaging system monitors 5 million km^2 of rainforest. Together, these tools enable large-scale ecosystem mapping and enforcement, helping to identify and protect high-value ecosystems and thereby inform where biomass production could be sustainably expanded (OECD, 2015).

5.5.6 Diversifying bio-carbon sources

To meet sustainability goals, research must investigate new, reliable, and available bio-carbon sources, including both virgin and waste feedstocks. Diversifying these raw material inputs is key to minimizing costs, ensuring resilience, maximizing efficiency of conversion from raw material to feedstock, and addressing land-use constraints by maximizing waste feedstock use. Potential raw material sources of bio-based feedstocks include:

- Vegetable oils like sunflower and rapeseed, which are especially relevant for markets where they can be grown locally.
- Crassulacean acid metabolism (CAM) plants, which can grow on land unsuitable for agriculture, thus overcoming land-use limitations (Collett et al., 2021a,b).
- Algae, which is already used on an industrial scale in food, biofuels, fertilizers, and pharmaceuticals (White and Ryan, 2015).

While palm and coconut oils naturally contain the C12–C14 fatty acids ideal for surfactants, other vegetable oils have slightly longer chains (Hayes et al., 2019). Therefore, novel techniques are needed to convert both virgin and waste oils into the desired carbon chain lengths at a large scale. Genetic engineering could also improve efficiency by making plants richer in specific fatty acids or sugars.

Although waste feedstocks typically have lower greenhouse gas emissions because no emissions are allocated to their cultivation, they are mostly composed of cellulose and hemicellulose. These require further processing to obtain sugars, leading to lower efficiency around ~60% and a greater need for feedstock (Chandel et al., 2018). In contrast, crops like sugar beet and sugar cane are high-yielding (12.5 and 11.0 tons/hectare, respectively) and their sugars are easily extracted with close to 100% efficiency (Philippsen et al., 2014). The optimal carbon source must be carefully considered across its entire lifecycle, a topic that lacks sufficient academic literature. A combination of first and second-generation feedstocks, utilizing all parts of a plant, may offer the highest yield of fermentable sugars.

5.6 Capacity building

5.6.1 Formation of an international body for sustainable formulations

As the global net-zero transition accelerates, industry coalitions have formed in hard-to-abate sectors to collectively improve sustainability. The Science-Based Targets Initiative (SBTi), part of the "We Mean Business" coalition, is one example that assists private organizations in setting science-based targets. Similar platforms for net-zero strategy collaboration could be provided by organizations like the International Council of Chemical Associations, though their scope is often broad.

A collaborative, multi-sector approach to policy development is needed, along with governmental guidance to ensure supply meets demand. Government support for low-carbon alternatives signals to the private sector the importance of developing and implementing net-zero policies. Multinational enterprises can facilitate this by applying successful policies from one jurisdiction to another. While carbon pricing policies may vary by region, sharing lessons from implementation can accelerate the transition. Carbon leakage can be mitigated via border adjustment mechanisms, bilateral climate clubs (Helm, 2015; Helm et al., 2012; World Bank, 2022), or regulations on multinational corporations' procurement.

Industry forums like the Consumer Goods Forum can facilitate coordination on standards and help companies identify the support they need to transition. The SBTi, a partnership between CDP, the UN Global Compact, WRI, and WWF, is a leading voice in setting standards for companies to align with the Paris Agreement and net-zero goals.

5.6.2 Workforce upskilling and employment

The chemical industry is a significant employer, representing the fourth largest industry in the EU and accounting for approximately 7% of its manufacturing output (European Commission, 2023a). It directly employs 1.2 million highly skilled workers, indirectly supports an additional 3.6 million jobs, and contributes to 19 million jobs across other supply chains within the EU (European Commission, 2023a). The industry's labor productivity is 67% higher than the manufacturing sector average (European Commission, 2023a).

Stakeholders have raised concerns about a potential future shortage of skilled workers for the transition to sustainable carbon. To address this, new and effective training approaches are crucial for rapidly integrating workers into the job market. These could include expanding access to relevant academic programs, offering educational incentives, promoting skill development through training-related mobility, and implementing reskilling programs for workers in adjacent sectors (Zhou et al., 2022).

According to a 2022 report by SystemIQ and the University of Tokyo, a decarbonized chemicals industry could create an additional 29 million jobs globally by 2050 (SystemIQ, University of Tokyo, and Center for Global Commons, 2022). This would more than offset the estimated loss of approximately 5 million fossil fuel sector jobs (IEA, 2022a). The transition of the FMCG sector would contribute to this demand for sustainable chemicals and the associated jobs.

5.6.3 Upscaling renewable energy infrastructure

For bio-based feedstocks to be considered sustainable, their production must be powered by renewable energy. This is a crucial factor, as ensuring all energy requirements including those for transportation and heating are met with renewables can significantly lower the emissions of bio-based formulations. For instance, the production of one ton of surfactant from sustainable feedstocks requires, on average, 14 kWh of energy (Schowanek et al., 2018). Continued promotion of renewable energy integration and capacity expansion globally will help achieve this goal, particularly given the increasing cost-competitiveness of renewables (Ritchie et al., 2024).

6 Discussion

While policymakers will need to address multiple considerations in formulating a sustainable carbon strategy, one of the most important objectives will be learning rates capable of reducing the cost gap between bio and fossil feedstocks. Given that effective policies must be context-specific, the primary recommendation of this article is for governments to create and adapt their own sustainable carbon strategies to advance learning rates at pace and scale. These sustainable carbon strategies can consider, incorporate, and customize the policy recommendations outlined in this report to provide a clear roadmap for implementation across all relevant stakeholder groups.

6.1 Sustainable carbon strategy for cleaning products: policymaker considerations

Addressing the barriers to a sustainable carbon market requires a range of policy options on both the supply and demand sides. Policymakers can adopt a structured approach when developing a sustainable carbon strategy and a baseline scenario for a given context, which should include the following elements:

- Staged policy implementation: assess which policy instruments are most suitable for different stages of market development.
- Trade-off analysis: identify common trade-offs in policy implementation and determine the optimal balance of outcomes.
- Synergistic interventions: identify where interventions are complementary to maximize the efficiency of policy efforts.
- Stakeholder coordination: determine the range of stakeholders with whom to coordinate for different policy interventions.

Alongside policies targeted at supply and demand, interventions designed to accelerate innovation are well-grounded in both economic theory and real-life success cases for building alternative supply chains. Successful instances of new technologies displacing older ones and achieving widespread adoption have involved the existence or creation of favorable initial conditions. A critical precondition is the existence of some type of emerging market opportunity for the new technology (Clark et al., 2021). For example, the transition to renewables in UK power generation and the ongoing push to electrify end-use sectors were significantly supported by policy interventions to enhance the commercial viability and market penetration of emerging renewable technologies (as illustrated in Figure 9).

These focused on reducing the price gap between fossil and renewable technologies through R&D to lower costs. Most of today's mainstream renewable technologies, including onshore and offshore wind, rooftop solar photovoltaic (PV), and concentrating solar power (CSP), have progressed to the top-right of the technology diffusion "S" curve (Stages 4 and 5), while newer technologies such as hydrogen from electrolysers, small modular reactors, and carbon capture, utilization, and storage (CCUS) are positioned at the bottom-left (Stages 1 through 3). An approach similarly focused on creating favorable initial conditions is desirable for accelerating the use of bio-based feedstocks.

The UK has also provided examples of how sudden shifts in policy, or the lack of clear medium-term signals, could harm progress. For example, the market for solar power in the UK slowed down significantly when policymakers reduced the subsidies to rooftop solar PV in 2010 by 65%, going on to close the scheme in 2019 while replacing it with other measures that did not result in a like-for-like incentive (Vieira, 2022). Similarly, the abrupt cancellation in 2015 of a £1 billion competitive capital budget scheme aimed at commercializing carbon capture and storage (CCS) technologies impacted innovation and industry and investor confidence, leading to a 10-year delay in UK capability to deploy CCS (Committe on Climate Change, 2016; Grantham Research Institute on Climate Change the Environment, 2023). The design of a sustainable carbon strategy, including for the FMCG formulations sector, ought to minimize such rapid shifts in policy or backtracking of critical commitments when possible.

These examples offer several key principles for policymakers crafting long-term strategies for the FMCG formulations sector, and beyond:

- Evidence-based baseline: establish baseline conditions for policy actions, such as the environmental cost of ozone-depleting substances under the Montreal and Kigali protocols, using evidence-based research and scientific findings. This provides the foundation upon which sectoral pathways can be developed.
- Policy perseverance: demonstrate sustained commitment once a policy or framework has been initiated to provide stability.
- Clear market signals: provide clear signals to both suppliers and consumers regarding the long-term nature of support measures to build confidence.
- Defined exit strategies: articulate clear exit strategies, specifying when and why support will be withdrawn. This could be due to insufficient progress toward commercialization or because technologies have successfully entered competitive markets (Foxon et al., 2005).
- Systemic view of innovation: understand innovation as a system and recognize the importance of "joined-up" or coordinated policies. These policies should support innovation through its various stages and, when necessary, be targeted to address specific barriers.

These principles show that a sustainable carbon strategy will have synergies with both circular economy goals and net-zero targets in relation to the environmental problems that these strategies address, as similar guidelines apply to these sectors.

6.1.1 Evaluating trade-offs in policy implementation

Policymakers in any context are likely to face a range of trade-offs when deciding which policies to implement, and in which combinations. We outline some key trade-offs below, applying to policy design more broadly beyond the FMCG formulations sector:

- Impact on lifecycle reductions of fossil-carbon produced by petrochemicals, vs. transaction costs of monitoring, regulation and verification systems. Effective policies to reduce emissions require robust quantification of sectoral lifecycle emissions and reporting these within a larger emissions accounting framework. There currently is no single, internationally harmonized method of monitoring, reporting, and verification for lifecycle emissions. Sectors and organizations have tended to provide their own guidelines and, for some technologies, analyses may even vary with geographical context (Nugent and Sovacool, 2014). A widely accepted and standardized system is required.
- Distributional impacts. Net-zero policies are likely to have distributional implications. For example, in the UK, "green" technologies have been supported through a levy on household consumer bills (called the "Environmental and Social Obligation"). For low-income households that spend a higher proportion of their incomes on "essential" goods, this may result in adverse distributional impacts—although revenues are recycled back into supporting these households or vulnerable consumers through compensation and grant schemes. Such impacts should be assessed and mitigated as far as possible.
- Political economy. The effectiveness of policies varies across national and regional political contexts. Policies that change relative prices (e.g., carbon pricing and taxation) may face public resistance, as they may be perceived by the public to be regressive, economically damaging, opportunistic and/or have a high personal cost. However, evidence shows that the method of implementation matters: for example, the use of trial periods (i.e., soliciting public feedback prior to institutionalizing a policy), tax escalators (i.e., the phase-in of a policy), environmental earmarking (i.e., hypothecating revenues to improve environmental living standards), lump-sum transfers (i.e., to mitigate distributional impacts on low-income households), tax rebates (i.e., cutting taxes elsewhere for revenue neutrality), and advanced communication strategies can help remove obstacles to implementation (Carattini et al., 2018).
- Revenue-raising vs. revenue-neutral policies. Fiscal policies designed for net-zero objectives often aim to generate revenue for green public spending and investment. Consequently, sectors with relatively inelastic demand, where consumer demand is not highly responsive to price changes, can be an appealing base for taxation. While a carbon tax can be regressive, its benefits should be evaluated by considering the ratio of welfare gains to tax revenue. This analysis helps determine whether the tax itself improves welfare, or if the welfare improvement is only realized when the tax revenue is combined with targeted public spending (Kotchen, 2022).

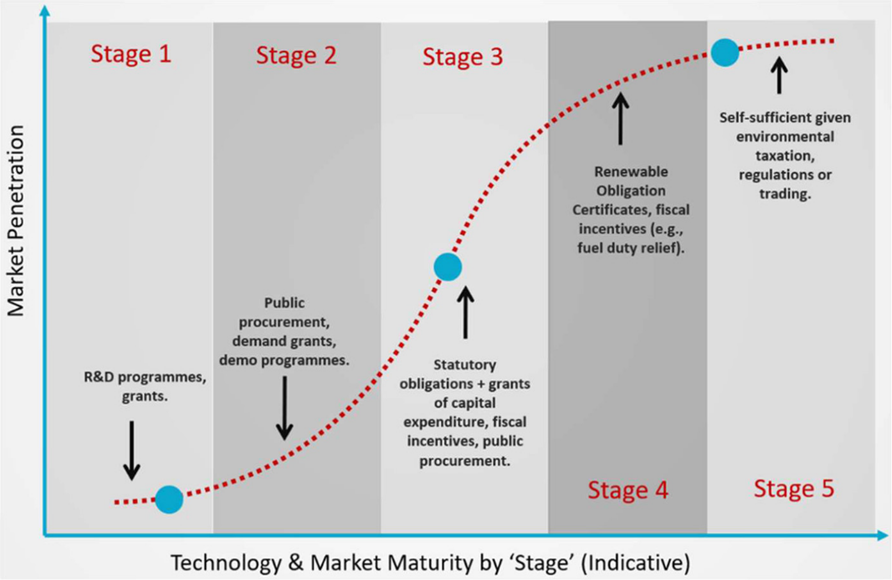

FIGURE 9
Indicative use of policy instruments to scale renewable technologies and market penetration in the UK. Source: Adapted from Foxon et al. (2005). "Stages" are illustrative/idealized.

- Unintended consequences. Unintended consequences tend to be very context specific. Considering bio-based formulations, potential consequences around land use, biodiversity, and social impacts should be particularly considered.

6.1.2 Considerations in the design of a carbon price: complementary interventions

Given contextually sensitive trade-offs, different policies and policy mixes will be appropriate in different jurisdictions. Given the urgency to act quickly, practical carbon prices alone may not be sufficient to drive the transition, necessitating the use of complementary policies (Hepburn et al., 2020). This is because politically feasible carbon prices are often too low to incentivize the necessary changes on their own, and because carbon prices should not necessarily be equal across countries to avoid slowing critical economic development pathways in low-income states (Hepburn et al., 2020).

Alongside carbon pricing, complementary policies can provide additional market signals and create positive spillover effects. For example, a carbon price combined with R&D investment incentives can catalyze the emergence of new sustainable feedstock sources or production processes (Institute for Fiscal Studies, 2021). Such incentives may be technology-neutral, to encourage a broad range of innovations, or targeted at specific early-stage technologies where there is a strong case for strategic support. Policymakers should take the full suite of policies into account alongside the national context when determining a sensible carbon price in formulations and consider a carbon price in line with existing prices rather than one representing the theoretical price that would be needed to tip demand from fossil-carbon to sustainable carbon (see Table 2). This implies selecting a carbon price at or below the lower end of the theoretical "tipping point" but supporting it with complementary policies.

TABLE 2 Potential considerations of carbon price.

Components of a price on formulations	Relevant effect	Impact on the tax rate
Baseline environmental damages	Sum of social costs of the carbon emissions	
Distributional concerns	Tax incidence approximately equal across households, although falls slightly higher on poorer households	–/neutral
Political economy	Appetite for carbon taxes as a policy mechanism	+ if exists, – if none exists
Tax component	Fiscal revenue generation: inelastic product can be taxed more before behavior is distorted	+
Land use changes	Shift away from agriculture to crops to produce from formulation	–
	Incentivizes deforestation	–

Source: Inspired by Funke et al. (2022).

6.2 Interventions across stakeholder groups

Recent experience has shown that coalitions built around specific environmental targets and SDGs can be a powerful driver of policy action. There are a broad range of stakeholder groups that are likely to be involved in enabling a pathway to net zero for household formulations.

- Policymakers: national, supra-national, and sub-national policymakers in government and parliament, who have the power to legislate and regulate net-zero policies, as well as implement packages of incentives to shift demand and supply toward sustainability and circularity.
- FMCG industry: sectors which rely on surfactants, including home care, personal care, industrial cleaning, textiles, food and beverages, plastics, and others.
- Financial bodies: central banks, development finance institutions, infrastructure lending institutions, treasuries, financial regulators and actuarial bodies seeking to reduce asset/portfolio exposure to climate risks.
- Non-governmental organizations (NGOs): advocacy groups and think tanks working on sustainable trade and development; environment; climate; poverty and inequality; health; and just transitions for workers in "sunset" industries (e.g., hydrocarbons).
- Research institutes: universities and publicly funded research institutions that conduct innovative research into innovative technologies, market opportunities, consumer behavior, policy designs and socioeconomic impacts of policy pathways.

Subsequent policy work could aim to map out the names of stakeholder institutions and their roles within the policy space of a particular jurisdiction in detail, with the next step being the establishment of a convening platform (for example, spearheaded by an industry organization or a multilateral organization) around the elimination of greenhouse gas emissions in household formulations as a critical part of the global drive to net-zero emissions by 2050.

7 Conclusion

This paper presents a portfolio of policy interventions aimed at decarbonizing the chemical formulations used in household cleaning and home care products, aligning the sector with the Paris Agreement. This requires replacing these fossil feedstocks with sustainable bio-based alternatives or permanently removing the petrochemical-based carbon from the atmosphere. The transition is unlikely to occur without policy intervention. The highly competitive FMCG market, characterized by low economic returns and the higher cost of bio-based inputs, makes it difficult for a single firm to switch feedstocks without incurring a competitive disadvantage. Policy is therefore needed to internalize the environmental costs of fossil-based inputs and provide structural support or regulation for bio-based alternatives. Policy may also be necessary to protect vulnerable consumers from price increases. A holistic framework is desirable to manage competition for bio-based feedstocks from other transitioning sectors, such as aviation.

Theoretically, a carbon price of US\$259–840/tCO_2eq is needed to make bio-based surfactants cost-competitive. However, aligning with existing carbon prices (Stiglitz, 2019; Stern et al., 2022) suggests a price at the lower end of this range is more practical. These prices may also vary across countries due to equity and economic structures (Hepburn et al., 2020; Stiglitz, 2019). A carbon price alone is unlikely to resolve all barriers, and reducing the cost differential will require additional policy interventions to incentivize innovation. Technological advances, spurred by policy, are crucial for achieving cost-competitiveness. For instance, while bio-ethanol is already cost-competitive, other bio-based options would need significant learning rates to compete with today's costs by 2050, underscoring the importance of policy in accelerating the transition. This paper discussed a portfolio of interventions aimed at both increasing the supply of and shifting demand toward sustainable carbon sources. Policymakers should strategically deploy these interventions in collaboration with stakeholders, to provide a roadmap for implementing sustainable carbon strategies and achieving a net-zero pathway for household formulations.

Author contributions

NS: Project administration, Formal analysis, Data curation, Methodology, Visualization, Investigation, Writing – review & editing, Writing – original draft. KC: Investigation, Visualization, Methodology, Formal analysis, Supervision, Writing – original draft, Writing – review & editing, Data curation, Project administration. CH: Funding acquisition, Conceptualization, Writing – review & editing, Supervision. AS: Writing – original draft, Project administration, Visualization, Writing – review & editing, Data curation. CW: Conceptualization, Supervision, Writing – review & editing, Funding acquisition. EF: Investigation, Methodology, Writing – review & editing, Visualization, Formal analysis, Data curation, Writing – original draft, Project administration. SG: Visualization, Writing – original draft, Project administration, Formal analysis, Data curation, Investigation, Methodology, Writing – review & editing. GR: Methodology, Writing – review & editing, Investigation, Visualization, Project administration, Formal analysis, Writing – original draft, Data curation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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