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Sustainability by defossilization: from global insights to a closer look at Malaysia

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The overarching goal of global energy decarbonization, envisioned to combat climate change, should be coupled with material defossilization, which is just as crucial to target waste accumulation and fossil fuel depletion. However, current policies and regulatory frameworks often neglect this dimension, creating a loophole that allows stakeholders to exploit decarbonization narratives—diverting fossil fuels from energy to chemicals, alongside expanding both renewable and non-renewable power sources, resulting in a misleading green image and an unsustainable level of consumption. This situation is elicited by socioeconomic trade-offs, such as the risks of profit decline, job displacement, and diminished market competitiveness, which compel stakeholders to act in favour of immediate self-interest. To counter these pressures, there is an urgent need for clearly defined, fiscally driven policies that leverage the comparative advantages, natural resources, and technical expertise of different nations to realign incentives toward long-term sustainability. From a pragmatic standpoint, Malaysia, with its wealth of fossil and biomass resources, is well positioned to lead a transition from fossil-based to bio-based materials. Key enablers of this transition include setting clear priorities for high-value bio-based products, building green infrastructure, enhancing vocational education, providing financial incentives, and establishing supply–demand pricing mechanisms to support market stability and growth.

Sustainability spotlight

In the context of escalating waste generation and unsustainable fossil-based chemical production, our work offers a perspective on the transformative pathway toward defossilization. By shifting from fossil fuels to renewable biomass feedstocks and promoting integrated biorefinery models, we argue that developing nations like Malaysia can reduce carbon emissions, enhance resource efficiency, and bolster economic resilience. This sustainable advancement not only mitigates environmental impacts but also addresses critical supply-chain challenges in the chemical industry. Our perspective aligns with UN SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

The world of today generates 2 billion tonnes of waste each year,[1] with 80% of it being non-biodegradable,[2] requiring hundreds and some even thousands of years to break down naturally and completely vanish. With the global recycling rate lingering below 20%, far behind the rate at which waste is produced, humanity risks being increasingly surrounded by the very waste it creates. Much of this non-biodegradable waste comes from essential daily products, ranging from automotive components to household items like cleaning products, plastic bags, and furniture, whose biodegradability is hindered by the use of fossil-based chemicals that microorganisms can barely break down. Making matters worse, chemical production ranks among the world's largest CO_2-emitting industrial activities. The annual release stands at about 935 million metric tonnes of CO_2 eq. (5–6% of global greenhouse gas (GHG) emissions),[3] already more than the entire EU's emissions in 2024 (894 million tonnes of CO_2 eq.).[4]

Fossil fuels account for 95% of the feedstocks used in chemical production, giving them an extensive presence in consumer products and closely linking their use to the escalating demand driven by increasing population and urbanization.[5] In a paradoxical twist in this increasingly environmentally conscious era, while platform chemicals are being employed to build negative carbon technologies, such as polymer fibres for

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carbon capture systems and lightweight plastics for battery packaging, this effort highlights the palpable irony of patching up the damage while inflicting further harm, as the raw materials themselves are unsustainable. As the industry navigates mounting pollution and energy challenges, the risk of exacerbating climate issues and waste generation looms large if it fails to decouple from fossil fuels. Even though 194 countries have signed the Paris Agreement to limit global temperature rise, and at least 4100 of the world's largest companies have launched industry decarbonization initiatives, these can only alleviate operational emissions, but they are unable to address upstream emissions from fossil input and end-of-life emissions from incineration. A fundamental shift in feedstock to non-fossil sources of carbon remains largely voluntary and is inconsistently regulated across regions, leading to uncertainties and divergent effects. Overcoming these challenges will require coordinated policy intervention, targeted investment, and robust government incentives, alongside transparent, measurable, and traceable data systems to ensure accountability and enforcement. Malaysia presents a promising case study in this context, where it has a large bioresource reserve, a decade-long development of relevant bioproducts, and significant fossil wealth that could be leveraged to ease the socioeconomic tension of the transition towards adopting and scaling bio-based alternatives. However, whether the Malaysian government is taking the right steps and doing enough remains a critical question worth exploring to unlock the country's full potential. Defossilization is the essential task not only to support decarbonization but also to ensure long-term sustainability and resilience.

Bio-based *vs.* petrochemical dominance: the struggle for market share

The production of bio-based chemicals is far from new. As early as the 1910s, they were used to manufacture rubber tires, pharmaceuticals, explosive cordite, and biofuels, primarily driven by wartime necessity.[6] However, by the 1950s, the advent of low-cost, high-volume petrochemicals sidelined bio-based routes, relegating them mostly to specialty niches, such as pharmaceuticals and biotech compounds (*e.g.*, DNA recombinants).[7] Despite more than a century of development, bio-based chemicals still account for less than 5% of global output.[8] Many of the industrialized bioproducts today are "drop-in" alternatives, like methanol, ethylene, and propylene, which can be incorporated into existing gasification processes. More ambitious fossil-free routes now allow biomass to serve as a feedstock for a broad range of commodity chemicals and polymers (Fig. 1), achieving up to 90% reductions in emissions due to lower processing temperatures and pressures.[9]

So why, after a hundred years and with technological feasibility no longer in question, do bio-based chemicals remain on the periphery of global production? The answer lies in the entrenched dominance of fossil-based systems. Although decarbonization efforts have begun to erode their structural, economic, and policy advantages, the lack of coherent policies, modernized infrastructure, and regionally aligned cost competitiveness continues to hinder the widespread adoption of bio-based alternatives.

The EU is the world's largest and longest-standing chemical producer, led by major bioeconomies, such as Germany, France, Italy, Poland, and the Netherlands, which are pioneers in both fossil-based and bio-based sectors. Nevertheless, over the past decade, the EU's share of the global chemical market has declined by 11%, driven in part by its aggressive push towards climate neutrality and circular economy goals, causing rising energy costs that outpace the revenues and demands of bio-based chemicals.[11] Moreover, EU countries have limited domestic biomass availability, and they import 51% of its biomass just to sustain even the current production of a mere 3% of their chemicals.[7] This reliance raises concerns about feedstock security and cost volatility due to seasonality and logistics, as well as the question of food competition when sourcing biomass. Building bio-based value chains further compounds the challenge. The seven major chemicals (methanol, ethylene, propylene, butadiene, benzene, toluene, and xylene) drive over 90% of downstream production and are deeply rooted in mature fossil-based technologies.[12] While drop-in bio-alternatives exist, they require modifications to existing processes, whereas more transformative bio-based routes demand substantial capital investment in new equipment, technical expertise, and innovation. Adding to the difficulty is market resistance, in which many bio-based products face higher production costs than their fossil-based counterparts, and in cases involving functional replacements or novel bioproducts, customers often hesitate due to unfamiliarity or uncertainty about performance.[13] This market hesitance further complicates the adoption and scaling of bio-based alternatives.

China, after absorbing the EU's lost market share, has now emerged as the world's largest chemical producer. Nevertheless, this ascent is underpinned by heavy reliance on coal-based feedstocks, which runs counter to the global defossilization effort.[14] To make matters worse, China's coal power construction approvals have surged to a 10-year high,[15] in which the country is attempting to offset emissions by simultaneously scaling up renewable energy generation. However, this parallel growth of renewables and fossil fuels reveals a fundamental disconnect: when defossilization is not holistically integrated into decarbonization strategies, climate commitments risk becoming a counterproductive patchwork. The ramping up of renewables has also prompted many domestic chemical producers to double down on fossil-derived production, viewing it as a lifeline for the continuity of their business.[16] Although the Chinese government has also shown support for bio-based products, such as bioethanol and biopolymers (*e.g.* PLA and PBS),[17] the scale of this effort pales in comparison to its continued expansion of fossil-based chemical production.

To better understand these dynamics, consider how oil displaced from the energy sector by the rise of biofuels is now being funnelled into the chemical industry. Major oil and gas companies, such as Exxon (US$20 billion), CPChem (US$14.5 billion), and Dow (US$10 billion), are heavily investing in downstream petrochemical expansion.[18,19] This simply shifts

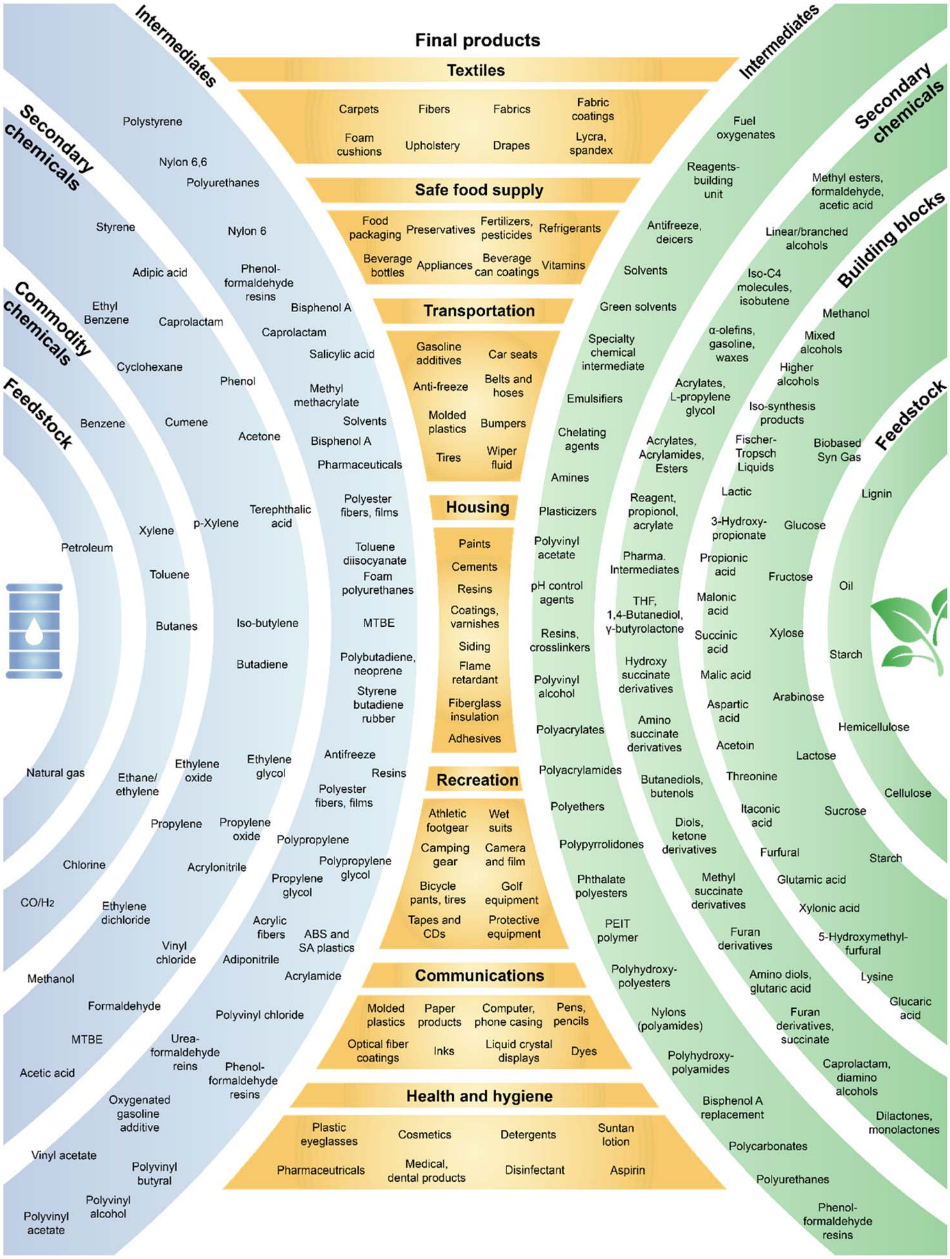

Fig. 1 Flow chart of products derived from fossil-fuel-based and biomass feedstocks.[10]

upstream emissions from one sector to another, rather than reducing them, exposing a major blind spot in current sustainability efforts. To close this gap, strong policy frameworks and strategic investments that redirect capital away from fossil-based production toward sustainable materials and technologies are required.

Industries in the EU and Japan have also started actively pursuing the production of "e-chemicals", generated from green hydrogen through electrolysis and captured CO_2 as fossil-free alternatives.[20] Nevertheless, significant barriers associated with high energy consumption remain in scaling up "e-chemicals", which should be viewed only as a complement to bio-based chemicals within an integrated biorefinery framework, where the availability of sustainably-produced e-chemicals is permitted. New energy-saving technologies are not a panacea; rather, decisive action leveraging existing, proven resources is critical to avoid foreseeable consequences—such as sea level rise—that we are already witnessing today as a result of delayed decarbonization efforts. Regrettably, many governments still overlook the value of coordinated policies and mutual support in addressing the biomass supply chain and cost challenges, particularly for countries with a long history of fossil-based chemical production.

Where does Malaysia stand?

Dominating a 22% share in the Southeast Asia wood pellet market in 2023,[21] Malaysia is no stranger to the biomass scene. A total of ~RM 1 billion in accumulated investments were injected into biomass-related projects during the Eleventh Malaysia Plan spanning 2016 to 2020, and targeting RM 10 billion total investment in the Twelfth Malaysia Plan, 12MP, from 2021 to 2025.[22] Thus far, pellets converted from woody, oil palm trunk (OPT) and oil palm frond (OPF) biomass, are utilized mainly for energy applications, such as boiler fuel and biomass power plants in Malaysia. A total biomass power generation capacity of 440.5 MW has been installed (1.2% share of total electricity generated in the country), with 70.65 MW contributed by grid-connected power plants, achieving a reduction in GHG emissions of 395.22 Gg CO_2 eq. (12MP).[22] Future growth is expected as local energy giants (*e.g.* Tenaga Nasional Bhd.[23] and Malakoff Corporation Bhd.[24]) have extended investigation of the feasibility of unconventional fuel pellets derived from oil palm empty fruit bunch (EFB) for co-firing. The flourishing of biofuel production is also supported by the export demands of diverse commodities, such as palm kernel shells (PKS), wood, EFB and OPT-derived pellets from Japan and the Republic of Korea.

While the progress made is nothing short of auspicious, Malaysia is only scratching the surface with merely 15% of the available biomass utilized. With its primary usage as fuel, biomass with high calorific value is inevitably in high demand. For example, PKS with the highest calorific value among oil palm biomass (Fig. 2a),[25,26] has an overall utilization rate approaching 100% from export and local cogeneration demands. In contrast, components with lower calorific values, like EFB, showed a utilization rate lower than 50% (National Biomass Action Plan, NBAP 2023–2030).[27] The solution to this imbalance in biomass utilization is parallel development in both energy and material extraction applications. Different types of biomass components are characterized by different intrinsic properties and are therefore suitable for different applications. Hence, the question is not, how do we increase the utilization rate, but rather, how do we effectively utilize them each to their advantage?

Aside from lower calorific value, EFB is generally plagued with a high moisture content of up to ~70%,[29,30] which reduces

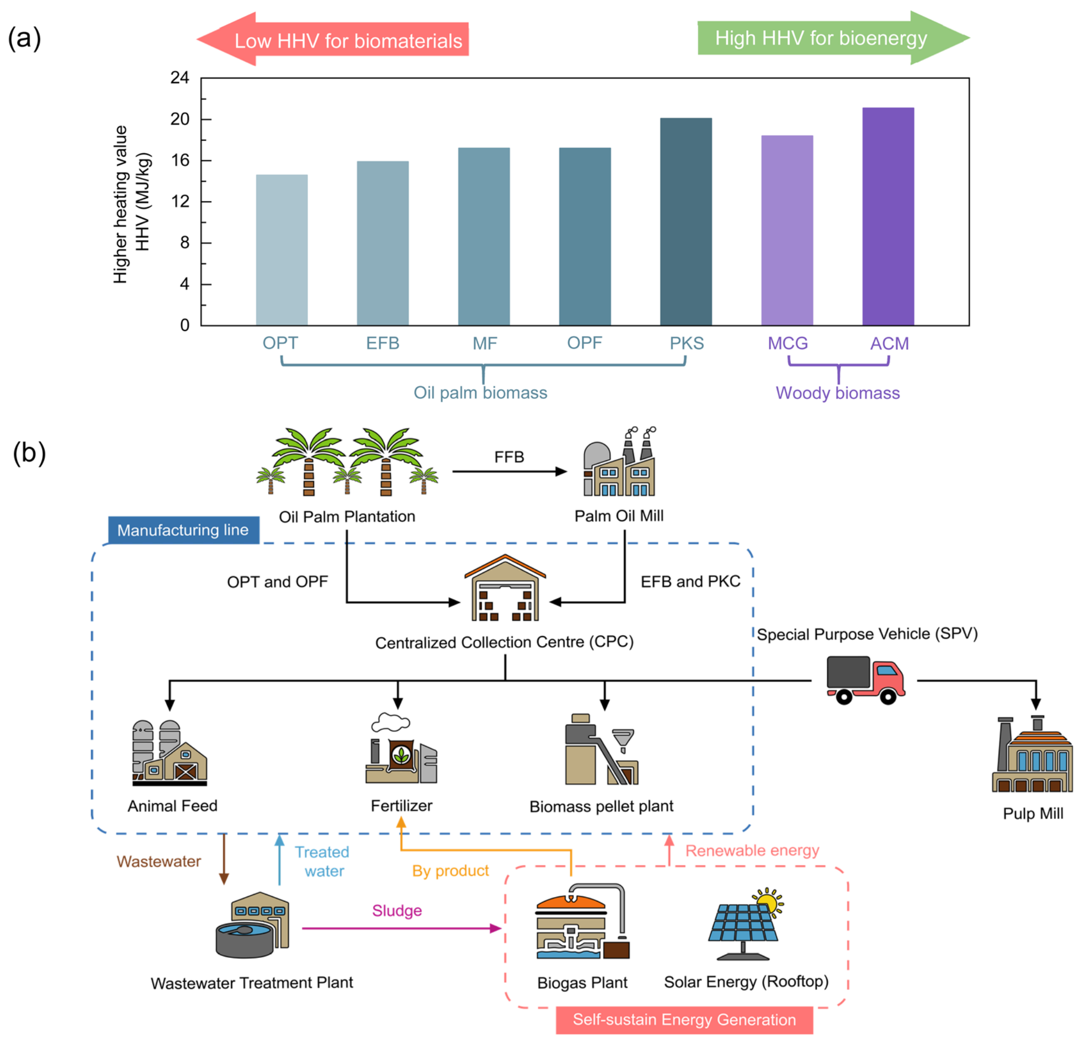

Fig. 2 (a) Higher heating value (HHV) of common oil palm and woody biomass in Malaysia.[25,26,28] (b) Logistic network for palm biomass centralized collection centres (CPCs). (Reproduced from National Biomass Action Plan 2023–2030 with permission from Ministry of Plantation and Commodities, copyright 2023).[27]

flame temperature and delays combustion, leading to higher fuel consumption and emission.[31] This calls for a paradigm shift away from the common association of biomass with energy conversion. Instead of trying to fit a square peg into a round hole, it is beneficial for research, development, commercialization and innovation (R&D&C&I) efforts to be directed towards matching inherent biomass characteristics to their suitable bioconversion routes. Leveraging the high cellulose content of EFB (23.7–65.0%),[32] fibre extraction for use in nanocellulose and paper pulp production, as well as cement reinforcement fillers, may prove to be a more lucrative option.[33–35] Other biomasses with greater higher heating values (HHV), such as OPF and woody biomass, could serve as superior biofuels (Fig. 2a).[28] However, such biomasses are available in remote forests and oil palm plantations, but the lack of logistical support for the collection of these biomasses in Malaysia has led to their severe underutilization. To address this, Malaysia aspires to establish a biomass hub, which would include the implementation of a logistic network that strategically connects oil palm plantations, mills, collection and processing centres (CPCs) and off-taker facilities *via* special purpose vehicles (SPVs) (Fig. 2b). Such networks should be further replicated for other underutilized biomass to facilitate their efficient aggregation with minimized transportation costs and GHG emissions.

It is also due to logistical issues that a large proportion of raw biomass in Malaysia is either not collected or recycled back to the plantations, for the purpose of mulching and soil enrichment. Unfortunately, without auxiliary soil amendments, it is often the case that mineralization of these organic wastes is not effectively retained and absorbed. Biochar can be derived from these biomasses and integrated with mulch to maximize nutrient absorption and retention through its porous structure, improve soil properties, stimulate microbial activity and foster carbon sequestration. Numerous studies have proved that the addition of biochar into mulch can enhance the growth of crops like maize, potentially reducing the amount of mulch required.[36,37] As of 2022, all agricultural wastes from banana and pineapple production in Malaysia, totalling ∼1.5 million tonnes, are left to decompose as mulch in plantations (NBAP 2023–2030).[27] Upholding the concept of doing more with less, excess wastes from biochar implementation can then be converted into other bioproducts,[38] including fibre extraction for textile production and biochemical extraction, such as bromelain and xylitol for biopharmaceutical products.[39,40]

Acknowledging the importance of balancing advancements for both biomaterial derivation and bioenergy generation, Malaysia is highlighting key targets of increasing the capacity of biorefineries to 3.5 billion litres and power generation capacity from biomass and biogas to 1.4 GW by 2050, through the National Energy Transition Roadmap (NETR).[41] While the manufacturing of numerous bioproducts is well established in Malaysia, *e.g.* biofertilizers, woody biomass-derived plywood, and bio-based food packaging, many sectors still remain immature. Specifically, at Technology Readiness Levels (TRL) of only 2 to 5 (NBAP 2023–2030),[27] the extraction of biochemicals and biopolymers requires concentrated R & D & C & I efforts.

Developing the nation with a heart of sustainability

Despite the question of "Can developing countries afford to go green?", Which is still commonly asked, Malaysia is currently in a position where everything is aligned, but it lacks a holistic strategy to guide coordinated initiatives with prudent resource management and distribution. It might be challenging, but not impossible, to simultaneously grow the national economy while ensuring compliance with sustainable standards. A whopping RM 6 billion was spent by Malaysia on animal feed imports in 2022, where 60–70% of the rising prices of domestic produce, such as meat and eggs, were contributed by feed cost (NBAP 2023–2030).[27] Biomass, like locally-sourced palm kernel cake (PKC), can be processed and blended as feed additives to reduce feed imports and the resulting produce prices,[42] strengthening the national economy. However, ∼98% of PKC in Malaysia is exported annually, generating revenue of ∼RM 1.7 billion, a number that could potentially be trumped by cost savings from reducing animal feed imports. It is timely for Malaysia to re-evaluate its utilization, taking into account economic, social and governance (ESG) considerations alongside environmental impacts.

The prioritization of converting biomass into high-value products is crucial to serve as a successful economic thrust for Malaysia as a developing country. Additionally, skyrocketing global demand for these products nurtures the production scaling up of their bio-based counterparts, incentivizing rapid technological advancement. Beyond the realm of chemicals, advanced novel materials are witnessing market demands that are outpacing commodity chemicals,[43] with compounding growth rates soaring to 35.1% for graphene,[44] 22% for nanocoatings,[45] and 20.1% for nanocellulose.[46] While many of these innovations are currently utilized as additives or enhancers, they hold transformative potential, exemplified by their incorporation into concrete, which boosts mechanical strength, reduces drying time, and slashes carbon footprints by 30% while lowering costs.[47] Despite their remarkable potential, many advanced materials are predominantly sourced from fossil fuels, with methane for graphene[48] and acetylene for carbon nanotubes[49] being prime examples. Malaysia should learn from past climate mishaps with commodity chemicals, where retrofitting fossil fuel-dependent processes now requires twice the effort. A stitch in time saves nine, so Malaysia must invoke the principle of sustainability by design through pivoting towards alternative biomaterials in process designs, establishing a strong foundation for advanced materials manufacturing with green processes at its core. Innovative companies, for instance, Graphjet Technology Sdn Bhd, are at the forefront of pioneering ventures focused on the production of bio-based graphene/graphite. Recently, the world's only direct biomass-to-graphene production plant at 3000 tonnes per year was commissioned to cater to increasing global demand.[50,51] With Malaysia positioned as the top importer of artificial graphite (15.1% of world imports),[52] locally-produced bio-graphite/bio-graphene is set to meet the raw material demand of the booming semiconductor and battery industries.

These success stories are indicative that Malaysia is adapting well to the transition towards the proliferation of advanced biomaterials, but the majority of existing bioproducts are generic, highly substitutable and of low value. The values of various bioproduct categories can be arranged in a pyramid, where the higher the layers, the smaller the required biomass input volume and the higher the market value (Fig. 3a).[53] Malaysia's overemphasis on bottom-tier production of bioenergy and biofuel will eventually lead to a vicious cycle of interrelated problems, impeding further growth in the biomass sector (Fig. 3b). Limited access to high-value-added processing technologies and technical know-how has forced businesses to venture into low-value bioproducts. As more businesses enter the market, biomass feedstock supplies dwindle, leading to unstable biomass pricing and challenges to secure long-term supplies. The low market value of these bioproducts drives the lack of incentives to continue operation, causing the rapid entrance and exit of market players. This portrayal of the biomass industry as non-sustainable undermines institutional confidence to finance related projects, and recurring capital shortages hinder investment in advanced biomaterial processing equipment and technologies.

Aside from scattered efforts and initiatives driven by the private sector, Malaysia needs comprehensive and cohesive plans to revolutionize practices across entire bioproduct supply and demand chains. In terms of supply, Malaysia offers

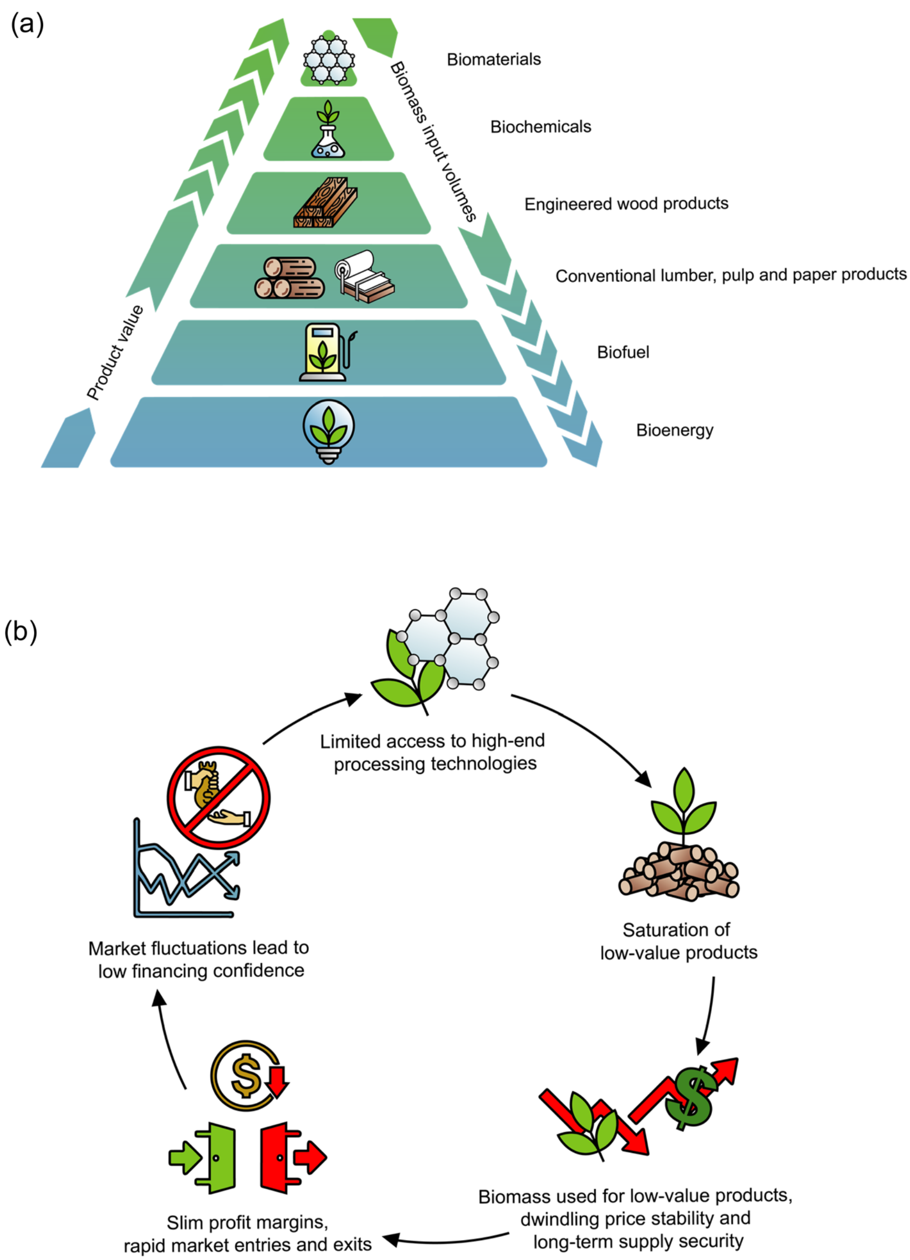

Fig. 3 (a) Value pyramid of bioproducts.[53] (b) Illustration of the vicious cycle leading to stagnant bioproduct development in Malaysia.

abundant funding opportunities, including the Green Technology Financing Scheme (GTFS) 4.0,[54] funding schemes from Development Financial Institutes (DFIs) such as Agrobank[55] and SME Bank,[56] as well as the INDUSTRY4WRD Intervention Fund for the adoption of industry 4.0 technologies in green projects.[57] It is crucial for Malaysia to look beyond financing. For instance, the United States has established the Bioenergy Technologies Office (BETO) that develops and compiles design cases for bioenergy production with in-depth analysis encompassing the effects of feedstock production and conversion technologies, pinpointing hotspots impacting production cost and efficiency, to be targeted by R&D&C&I investments (BETO 2019 R&D State of Technology).[58] Thailand is in the midst of forming the Eastern Economic Corridor of Innovation (EECi),[59] where it serves as a biopolis complex providing green technologies that are freely available under patent law and widely disclosed for adoption by academic institutes and companies. Taking global policies as examples, the next step for Malaysia is to get investors and businesses ready to penetrate new bioproduct markets by equipping them with the necessary knowledge and training.

Purely supply-side strategies create demand–supply inequilibrium, and thus, should be levelled by demand-side efforts. The lack of Malaysian governmental intervention on fluctuating prices of biomass feedstocks may not only lead to unstable revenues for bioproduct producers[60] but also dampen demand, as feedstock costs are also reflected in unstable market values of the bioproducts. China addresses this by implementing a biomass energy pricing policy that regulates the price floors and ceilings of biomass feedstocks according to market conditions and transportation costs, which could be similarly introduced in Malaysia. Nonetheless, all efforts would remain futile if there was misalignment between the consensuses of producers and consumers, where what is produced is not what is wanted, bringing about inefficient resource allocation. The United Kingdom (UK) has proposed building a priority list for high-value chemicals converted from biomass feedstocks.[61] Such an idea could act as a blueprint to design biomass conversion maps that would guide businesses to prioritize channelling biomass resources into high-value products with ready mass demands, based on collated demand information and feedstock availability. After product development comes quality assurance, and the drastic characteristic variation common to biomass feedstocks means that insufficient benchmarks for standardising quality remain a major deterrent to confidence in bioproducts. To tackle this, inspiration can be taken from China's multi-tiered system of standards for biofertilizers,[62] which establishes guidelines on feedstock qualities as well as physical, chemical and biological specifications for biofertilizers to be sold in the market.

The Paris agreement for materials

There is no better testament to the diligence of Malaysia as a small developing country, than its dedicated initiatives and proactivity towards green transition. Being a country that is richly blessed with resources not only from the past (fossil fuels) but also for the future (biomass), Malaysia has cushions at both ends of the spectrum to reduce risks from energy and material security, streamlining the transition with minimal disruption to national productivity. However, the country's unrelenting but uncoordinated efforts in green transition is like sailing a ship stocked with treasure but with no one at the helm. It was not until the implementation of the Paris Agreement in 2016 that systematic guidelines and regulations emerged to address global issues. The agreement clearly outlines the goal of limiting global temperature rise to no more than 1.5 °C above pre-industrial levels. Participating countries' action plans are reviewed every five years to ensure progress, using specific metrics like carbon intensity (the amount of CO_2 equivalent emitted per dollar of GDP) and carbon pricing to measure commitments. While the primary scope of the Paris Agreement is to combat climate change, fossil fuel depletion and waste accumulation are equally critical global exigencies that raise the question of whether we need another international treaty with material defossilization as the focal point, analogous to the Paris Agreement, but exclusively associated with carbon emission reductions.

Such a treaty requires the laying down of a precise, systematic framework and clear policies for quantifying non-renewable and non-biodegradable materials, mirroring the current carbon footprint quantification. This framework should include well-defined metrics, phased goals, and robust tracking mechanisms to effectively prevent waste and resource depletion. In this context, the "Malaysia Plastics Sustainability Roadmap 2021–2030"[63] focuses primarily on increasing recycling rates and value retention, which is more of a cleanup strategy rather than tackling the problem at source. Japan's 2019 Resource Circulation Strategy for Plastics, instead, exemplifies a "3Rs + Renewable" principle, introducing a fourth "R" for renewable resources, emphasizing the need to embrace renewable materials while phasing out fossil resources to prevent future problems. Parallel to this is the concept of "enough", as more companies produce green products like bioplastics and biostraws to fulfil consumers' eco bona fides, often overlooking their functionality and the fact that these items can degrade too quickly to offer sustainable solutions, thereby requiring increased production to continually replenish them. Excellent values were conveyed by the Austrian government on this, where they pursue the status of "sustainable consumption" by advocating "sufficiency" in consumption behaviour, "efficiency" in raw material utilization by production decision making and "consistency" in recycling and circular economy management. The fact that steps taken by countries around the world towards greening the Earth have sprung more from accountability rather than being bound by statutory instruments, speaks volumes regarding the significance of human decency and self-awareness in determining the success of these steps.

Adopting the correct mindset, rigorous efforts can be directed towards vital areas explicated in this perspective. Defossilization of entire chemical supply chains with bioderivatives and "e-chemicals" is presented as a single solution with multiple objectives, including minimizing GHG emissions and energy consumption owing to milder processing conditions, smoothing the transition to renewable resources to mitigate fossil fuel depletion, and reducing the environmental persistence of generated wastes. Parallel development in diversified bioconversion routes of different biomass types facilitates the alignment of the inherent properties of biomass to their respective appropriate applications, for effective utilization in both energy and material advancements. This demands the establishment of an auxiliary infrastructure, such as a systematic logistic network for efficient biomass aggregation. A paradigm shift to prioritize high-value bioproducts is also crucial to allow developing countries like Malaysia to simultaneously engage in economy-boosting initiatives while actively participating in the global sustainability movement. Such development efforts must be catalyzed with a comprehensive plan including both supply-side and demand-side bioproduct supporting policies.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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