Towards a circular bioeconomy from bioenergy status quo policy: Providing evidence for implementation in Mexico

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Abstract

A circular bioeconomy revolutionizes resource usage by integrating sectors and systems, creating renewable carbon-based products and bioenergy through biorefineries. It's a game-changer for energy transition and sustainable development. However, biorefinery and bioeconomy policies are often overlooked, hindering progress. This study fills the policy gaps, offering crucial data and schematics to guide decision-making worldwide. It demonstrates the case of Mexico by employing three methods: 1) Mexico policy analyses, 2) a specialist workshop to gather evidence, and 3) grey literature analyses to show biorefineries in Europe and other parts of the world. A systemic approach is needed to achieve a sustainable circular bioeconomy, with biorefineries leading the charge in addressing climate change, biodiversity loss, and resource depletion. By optimizing biomass utilization and implementing bioeconomy policies, we can create a better future while uplifting marginalized communities and ensuring resource security.

Keywords: Mexico's National Development Plan 2019-2024 (PND), Transition Strategy to Promote the Use of Cleaner Technologies and Fuels (Energy Transition Law LTE) by the Ministry of Energy (SENER), European biorefinery outlook 2030, waste biorefinery, bioeconomy, policy.

1. Introduction

Globally, over 80% of the energy supply is from fossil fuels. Bioenergy meets just over 6% of the world’s energy demand. 75% of Mexico’s energy mix is fossil energy [1]. However, Mexico is rich in biomass residues. Agricultural and forestry residues amount to 38 and 1.4 megatons of dry matter per year (Mt DM/y) with an energy potential of 670 PJ/y and 31 PJ/y [2]. The excess agricultural and forestry residues can provide 6% of the national energy mix compared to the current bioenergy proportion of 2% of the energy mix [1]. The use of fossil resources contributes to greenhouse gas emissions (GHG), the main cause of global warming potential. Biomass residues that are available in excess can provide bioenergy in a community-led combined heat and power system configuration [3]. As biomass sequesters carbon dioxide during growth, the carbon dioxide released during combustion of the biomass to recover heat into high pressure superheated steam generation expanded through an expander attached to a generator to generate electricity is captured during biomass growth, thus giving an overall carbon neutral performance [4]. If the life cycle is considered, there would be some carbon footprint, e.g., from logistics; however, bioenergy’s carbon footprint is far less than fossil energy’s [3,5,6]. Furthermore, carbon capture, and storage (CCS) from bioenergy give carbon-negative performance meaning that the energy generation is associated with net GHG reduction from the atmosphere [3,7]. CCS would incur a 20% loss in energy efficiency and a 20% increase in capital investment [8]. Bioenergy with CCS (BECCS) is a way forward in many countries’ net-zero policies [9,10,11]. BECCS can remove 0.5-5 Gt/y carbon dioxide from the atmosphere at a cost of USD100-200/t [10]. BECCS using biomass residues can achieve a 66% reduction in atmospheric carbon dioxide with 87% large-scale deployment [11]. The Emissions Gap Report 2021 shows that to keep global warming below 1.5 °C this century to avoid global climate catastrophe, the world needs to halve annual GHG in the next eight years [12,13]. Thus, bioenergy and BECCS could contribute to the GHG reduction needed to achieve net zero [13]. Net zero is when the amount of carbon dioxide equivalent (CO_2e) emitted into the atmosphere due to human activities equals the amount of CO_2e removed from the atmosphere over a specified period [13]. Although this net-zero definition has been adapted from the IPCC [14], we emphasize accounting for all GHG; CO_2e accounts for all greenhouse gases represented in terms of carbon dioxide equivalent [13]. Greenhouse gases are carbon dioxide, methane, nitrous oxide, substances controlled by the Montreal Protocol, hydrofluorocarbons, perfluorinated compounds, fluorinated ethers, perfluoropolyether, hydrocarbons, and other compounds [13,15]. Global warming potential is calculated by the integrated radiative forcing of an emitted greenhouse gas relative to carbon dioxide [7,13]. The unit representing the global warming potential of greenhouse gas is the quantity of carbon dioxide equivalent (CO_2e) [7,13]. A decarbonization target for individual entities or systems can be set so that the aggregated individual targets offer the global net-zero or net negative greenhouse gas emissions when anthropogenic removals exceed anthropogenic emissions [1,13]. Indigenous biomass can play a key role in the practical implementation of biorefineries because they offer an opportunity to channel the cash flow to the much needy low-income population [3,4]. Earlier, we showed examples of bio-based economic activities for green inclusive growth and intensification of sustainable production and consumption pathways, for Malaysia [4]. In another study, we presented the life cycle sustainability assessment (ISO14040-44 and ISO26000), the United Nations Sustainable Development Goals (UN SDGs) and community-level indicators of bioenergy in Mexico [3]. The study also identified that one bottleneck for community-level distributed bioenergy generation is its maximum cap imposed by the national energy policy in Mexico.

We now discuss how the bioenergy and bioeconomy policy framework development has been addressed in the literature using scholarly resources. Methodologies and specific biomass resource-based or technology-based studies have been highlighted from regional/national to local scales to identify the key parameters to account for in a robust policy framework to support the development of biomass, bioenergy, biorefinery and bioeconomy (B4) systems. An econometric model was suggested based on Eurostat data for 23 EU members to assign an efficiency score to forestry economies considering environmental protection and social and economic development [16]. Their model was to maximize countries' forestry sector gross value added, considering the countries' natural and human capital and technical capabilities. Biofuels have been shown to benefit the agricultural sector in the following ways, (1) promoting a shift from wasteful annual crops to perennials, particularly low-input high-diversity crops; (2) sequestering carbon in soil both organically and as biochar; (3) improving conservative water management practices; and (4) recycling resources [17]. Solid biofuels, pellets, briquets and chars have been compared for the scale, heating value and social impacts between selected biomass-rich developing and developed nations [18]. The combined heat and power systems (CHP) with and without CCS have been considered for life cycle impact assessment to calculate their land requirements, in Mexico [19]. The electricity generation to land use calculated varies between 1.9 and 28.8 MW per hectare [19]. Considering the role of plants in food security, energy security, climate change and global environmental health, a joined-up policy governance approach has been recommended [20]. The role of biomass is seen in a massive scale of carbon dioxide removal from the atmosphere through forest biomass, soils, BECCS, ocean fertilizer and biochar, etc. [21]. Another study gives a landscape of fora, institutions, and processes to support bioeconomy and regional bioeconomy is a recommended way forward [22]. Coordination bringing the supply chain together makes an attractive economic proposition of levulinic acid and furfural (specialty chemicals) co-production [23]. A cascading approach to co-product choices, nanocrystalline cellulose, wood-based textile fibers, lignin-based products, chemical derivatives from tall oil and biochemicals derived from non-wood forest products, such as resin and tannins could promote forestry bioeconomy [24]. Biorefinery offers not only an integrated facility but also calls for symbiotic integration between the waste generator and biorefiner, for e.g., in tequila industry waste, agave bagasse is a lignocellulosic feedstock that can be processed into bioethanol, hydrogen (via dark fermentation) or methane production [25]. Another tequila industry waste, vinasses are a source of protein that can be extracted as animal feed with the application of yeast-based biotechnology lowering chemical oxygen demand, nitrogen and phosphorous contents of wastewater that are nutrients to grow the yeast [26]. Furthermore, Agave and Opuntia species naturally found in arid, semi-arid and dry sub-humid zones, covering 70% of Mexican territory have similar land productivity (43 dry t ha^{-1} year^{-1}) to herbaceous species (35), trees (39) and agronomic species (49) [27]. In the search for the literature on smart and sustainable bioeconomy platforms, a study used green economy, forest bioeconomy and blue economy, showing the wider implication of the bio-based excess available feedstocks [28]. The blue economy indicates the marine-based ecosystem that can be utilized for carbon dioxide sequestration. Many studies refer to microalgae and macroalgae-based biorefineries as part of the blue economy. However, if algae are to produce nutraceutical, pharmaceutical and personal care products, they need to be grown in a controlled environment to avoid potential contamination with heavy/toxic metals, etc. [29]. Algae grown in the natural environment are useful for bioremediation and recovery of heavy metal resources that could have had a detrimental impact on the environment [29]. The wild types can be used for bioenergy or biofuel generation. *Sargassum* recovered from coasts and beaches has been used as fertilizer

[30]. Driven by their large influx, alternative routes to bioenergy and biofuel generation via pyrolysis, gasification and hydrothermal conversions have been investigated [30]. Mexico with an Exclusive Marine Economic Zone of 3.15 million km^2 could have a large wet tonnage of over 20 million tons of *Sargassum* population [31]. Bioprospecting with an added-value approach is being applied to *Sargassum* in a blue bioeconomy context [31]. Another work also suggests this invasive species use to produce common energy vectors, bioethanol, biogas, bio-oil, biodiesel, biohydrogen, and biobutanol [32]. Another study investigated food supplement and thickening agent extraction from brown algae, biocomposite and biofertilizer extraction from green algae and food supplement and anticoagulant extraction from red algae, in addition to bioethanol extraction from all three types [33]. Like macroalgae, a plethora of research exists on microalgae valorization to produce biofuels, especially biodiesel, because microalgae are an oily feedstock that can be chemical-catalytically (trans)esterified in lower alcohol esters known as biodiesel [34,35]. However, like macroalgae [29], microalgae can be used for added-value productions, polysaccharides, lipids, vitamins and pigments, etc. for food, healthcare and personal care applications, or dyes, paints, bioplastics, biopolymers, and nanoparticles, or as hydrochar and biochar in solid fuel cells and soil amendments [36]. Although the utilization of biomass to produce added-value products in a cascaded manner, in the order of priority, from nutraceuticals, pharmaceuticals and healthcare and personal care products through commodity chemicals to biofuel and energy products has been recognized [13,29,37-39], energy security, climate change mitigation and limited capital availability have constrained the application of biomass processing technologies into biofuel and bioenergy production [40]. In Mexico, bioethanol production is supported by a mandated blend with fossil-derived transport fuel counterparts; regulation NOM-010-CRE-2016 allows the use of a blend of ethanol (5.85%) with gasoline in non-metropolitan areas. [41]. A study identified

nine barriers to biorefinery development for added-value productions; these are transportation/logistics cost and management, limitations on infrastructure and storage capabilities, lack of knowledge on valorization pathways, lack of financial resources/capital, overregulation or inadequate regulation, lack of demand-pull effect, cultural unfitness, seasonality of feedstock and (partial) lack of governmental support [42]. Amongst the nineteen challenges the study listed, the “need of investments to integrate biorefineries” is reinstated [42]. The lack of financial resources/capital, a prominent barrier to biorefining [13], has also been mentioned the most among all potential barriers identified [42]. Another study identified bio-resource availability, quality, logistic planning, economic, ecological, and social issues, policy, research and innovation as the main bottlenecks to biorefining [43]. The study suggested mainstreaming life cycle assessment and social impact assessment [43], which is comprehensively addressed elsewhere [3,6,7]. Another study reiterated policy, scaling-up, collaborations and appropriate business model gaps to the bioeconomy propositions [44]. Mexico’s National Development Plan 2019-2024 (PND) recognizes biomass as a clean energy source for populations and communities [45]. Renewable resources including biomass could provide clean electricity to small, isolated communities that still lack it, and which total some two million inhabitants [46]. Bioenergy features in the set of clean energy selections along with other options, wind, solar, geothermal, hydropower, ocean energy and CCS [47]. The main driver for bioenergy is sustainable environmental management. The National Inventory of Renewable Energies (INERE) estimated 436.8 MW of bioelectricity generation potential and 2786.62 GWh of annual bioenergy generation potential [47]. Yet, there is no strong incentive for biorefining and bioeconomy in Mexico. In promoting the future development of bioeconomy as an element that contributes to the development and socioeconomic well-being of the country, integrative infrastructure development is one aspect, in addition to the other two aspects of saving and efficient use of non-food unavoidable biomass; and in the lines of action, although the integrative infrastructure development has not been further elaborated. Mexico gets to legislate to support bioeconomy in line with the world.

To fill such policy gaps, this study shows comprehensively critical data and evidence for more clarities in policies on B4 systems. The policies evolve as novel technologies and systems are researched and developed and new data and evidence are generated. We, therefore, get to enumerate potential B4 schematics to provide data and evidence that will help to support B4 policymaking in any country or region. Promising schematics have been shown and evaluated to guide their selections and prioritize investments to support their sustainable developments in Mexico. The paper is structured as follows. The materials and methods section discusses the Mexico policy analyses, an approach to conducting a specialist workshop and grey literature analyses. The results and discussion show the key findings from Mexico policy analyses, key findings from the workshop and biorefinery/bioeconomy schematics, data and evidence. The final section draws on the main conclusions of the study.

2. Materials and methods

The methodology consists of Mexico policy analyses, an approach to conducting a specialist workshop to validate our policy analyses on B4 systems and grey literature analyses to show how bioenergy can be cogenerated within biorefineries, a key ingredient to the circular bioeconomy. These three are discussed as follows (Figure 1). First, the related Mexico policies [45,47] are analyzed to extract the essential points to discuss further at the workshop. Second, an expert workshop is held to gather evidence, which is further analyzed to synthesize the outputs. Third, grey literature is consulted to show biorefineries in Europe and other parts of the world. The results from the three approaches are discussed in the following section.

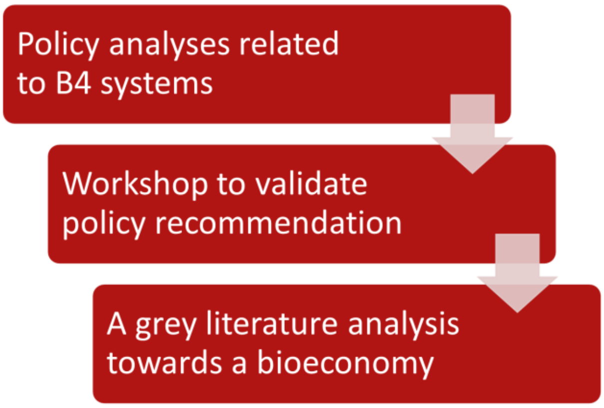

Figure 1. The methodology comprises policy analyses, a specialist workshop to validate policy recommendation, and a grey literature analysis.

Mexico's current policy analyses related to B4 systems: Mexico's National Development Plan 2019-2024 (PND) recognizes biomass as a clean energy source for populations and communities [45]. PND is a planning instrument to implement the energy transition as well as a transition strategy to promote the use of cleaner technologies and fuels. The polices in Mexico related to biomass and bioenergy systems are the Promotion and Development of Bioenergetics (LPDB) and Energy Transition Law. The first law defines and promotes the production of bioenergy, and the second law establishes the policies and goals for the energy transition through planning instruments. "Transition Strategy to Promote the Use of Cleaner Technologies and Fuels" (Energy Transition Law, LTE) by the Ministry of Energy (SENER) provide bioenergy-related actions [47].

The Wellbeing Programme within PND aims to benefit some 2.8 million small and medium-sized producers (up to 20 hectares), which make up 85% of the country's productive units, with priority for 657,000 small indigenous producers [45]. It channels productive support per hectare in advance of planting and promotes agroecological and sustainable practices, soil conservation, water and agro-diversity among producers; encourages self-sufficiency in the production of seeds and other inputs, as well as machinery and equipment appropriate to small-scale agriculture, and the implementation of renewable energy systems. A support of 1,600 Mexican pesos (MXN; ca. 90 USD) per hectare is given for plots of up to 5 hectares, and a thousand MXN (ca. 56 USD) for plots between 5 and 20 hectares [45]. There are some supports available for bio-based product development in the PND. For e.g., the support being granted aims to promote “the renewal of coffee plantations, the use of better genetic materials, the implementation of sustainable production practices, the addition of value and differentiation of their products and to the conservation and better use of soil and water and to the conservation of biodiversity.” [45]. Alongside supporting 250,000 small coffee producers, 170,000 sugarcane growers will also be supported. The coffee program aims at channeling productive support for an amount of 5,000 MXN (ca. 278 USD) per producer of up to 1 hectare, while the sugar cane program aims at supporting producers of up to 4 hectares who will receive direct support of 7,300 MXN (ca. 406 USD) per producer [45]. PND also mentions the distribution of environmentally friendly chemical and biological fertilizer, including the beginning of the operations of the fertilizer plants in Coatzacoalcos and Veracruz [45]. There are also price guarantees for corn, beans, bread wheat, rice and milk crops and livestock credit to the floor. The Mexican Food Safety Agency (SEGALMEX) has been created to coordinate the acquisition of agri-food products at guaranteed prices; sell and distribute fertilizers, improved seeds or any other product that contributes to raising the productivity of the field; promote both the industrialization of basic foods, milk and its derivatives, as well as the commercialization of surpluses from agri-food production inside and outside the country; promote the creation of micro, small and medium private companies associated with the commercialization of food products; support the tasks of scientific research and technological development that are linked to its purpose and distribute the basic basket in regions of high economic marginalization [45]. The agricultural sector is a strategic sector in terms of food security and the export of primary products. In 2017, the sector represented approximately 3% of the national GDP and 3.4% of the country's final energy consumption.

The actions for the regulations and public policy for bioenergy include strengthening the policy framework for the sustainable production of bioenergy, increasing investment certainty; establishing technical standards and regulations applicable to the production of bioenergy with sustainability criteria and with reference to quality and management, certification schemes and verification of their value chains; and harmonizing favorable legal frameworks for the energy use of urban waste and the recycling of materials, at all levels of government. The actions of the institutions include developing and implementing a national sustainable land use management system that promotes balanced and sustainable use of agricultural and forest land; strengthening institutional capacities for the application of the legal framework related to the production and use of bioenergy; promoting the use and acquisition of bioenergy in public sector companies. Technical capabilities and human resources are to develop training programs in planning and financing of processes and operation of more advanced technologies for pre-treatment, production, improvement and use of bioenergy; establish programs and/or institutions to professionalize certifiers and verifiers of sustainable value chains of bioenergy. The financing is to support rural communities that produce bioenergy, favoring the use of degraded land not suitable for food crops, facilitate access to financing for the production of sustainable bioenergy that favors the development of value chains, promote the investment necessary to attract biofuels to the market and evaluate the establishment of financing programs or incentives for municipalities and the private sector that use urban waste for energy. The research, development and innovation target to strengthen national and regional research capacities to take advantage of second generation bioenergy (from non-food biomass) and develop and strengthen the capacity for analysis of the economic and environmental impact of the production of bioenergy and their life cycles. Biomass providing heating, electricity and cooking fuel like the bioLPG has significant potential to increase energy supply in densely populated countries. Technologies converting biomass into energy commodities are efficient wood-saving stoves, biomass drying and roasting, biodigesters to produce biogas, pelletization, gasification to produce hydrogen and biotechnological, enzymatic and algal routes to biofuels. Rural solid wastes including those used for biogas generation are a way to alleviate the energy poverty of the communities. It can be noted that the agricultural sector, which contributed to 3.4% of the country's final energy consumption and 3% of the national GDP in 2017, includes agriculture itself (60% of the GDP contribution from the sector), livestock (30% of the GDP contribution from the sector) and fishing and forestry (3% of the GDP contribution from the sector), etc. [47].

Bioenergy has a role in the *Sovereign Energy Transition Scenario* (TES) in the “Transition Strategy to Promote the Use of Cleaner Technologies and Fuels” (LTE) by SENER [47]. The accelerated promotion of energy efficiency policies and measures will boost the self-sufficiency of the energy sector to stabilize the final energy consumption at 5480 PJ in 2050 (from the current consumption of 4654 PJ). In 2050, there will be a 43% reduction in the final energy consumption (5480 PJ in 2050) from the projected baseline scenario with 9621 PJ of total energy consumption. The most assertive strategy will be to accelerate and direct national energy efficiency efforts towards the transport and industry sectors, since these will allow reaching 84% of the reduction in final energy consumption by 2050. Another strategy will be to keep current energy efficiency policies directed to technological changes in equipment in the residential and commercial-services sectors, although these regulations and programs will have a moderate impact in the future. Mexico has prevented 5% of energy consumption by energy efficiency measures in the period of 2010-2018 and Mexico’s energy efficiency-related savings are better than the global average achieved by mandating energy efficiency policies for the building sector (both residential and commercial) and introducing fuel efficiency standards. The transport, manufacturing, residential, service, agricultural and construction sectors would bring reductions in energy consumption by 2258 PJ, 1223 PJ, 425 PJ, 168 PJ, 42 PJ and 25 PJ, thus a total reduction of 4141 PJ in energy consumption from the projected baseline scenario (9621 PJ) to the TSE scenario (5480 PJ). The GDP is expected to grow at 0.6 per annum during this period. The national goal in the medium term will be to reduce the final energy intensity (Petajoules per million pesos) to 2.2% between 2020 and 2035, and in the long term, it will be to reduce it to 2.5% in the period 2036-2050. Relating to the role of biomass, the use of recycling technologies for industrial waste and derived products, as well as the optimization of materials and raw materials, automation of manufacturing processes and implementation of cogeneration systems to take advantage of the simultaneous production of useful heat and electricity in the industry have been identified for the manufacturing sector transitioning. Clean energy generation, where bioenergy is featured alongside renewable, nuclear and CCS, will make up 35.1%, 39.9% and 50% by 2024, 2033 and 2050, respectively, according to the projection by SENER.

Conducting an expert workshop: The workshop on bioenergy policy and indicators in Mexico was held on 18th January 2023 in Mexico City. It followed an invitation to the network of policymakers of the Instituto Mexicano del Petróleo (IMP). Twenty delegates, 40% women and 60% men, including the authors, participated in half a day workshop. There were twelve academics, five industry/government participants and three Civil Society stakeholders. The workshop aimed to discuss B4 activities in the context of the current policy landscape and policy priorities. Stakeholders had the opportunity to contribute with their views and scientific, technical, social, or political expertise to policy recommendations and the selection of indicators relevant to the Mexican context.

Following a brief presentation by the authors to set the scene, a set of questions was posed to identify bioenergy and biorefining by local communities and private enterprises in the Mexican context. The questions are as follows.

1. Any market pulls towards bioenergy (biofuel blending mandated) and bioeconomy (e.g., communities generating bioenergy and extracting added-value products from local biomass)
2. Biorefining examples (e.g., biodiversity and high-value multi-product/multi-feedstock at what TRL, how can we push the TRL)
3. What bioenergy and bioeconomy policy/strategy do you want to have?
4. What can be done with the sugarcane sector? (170,000 sugarcane growers will be supported. The sugarcane program aims at supporting producers of up to 4 hectares who will receive direct support of 7,300 MXN (ca. 406 USD) per producer, according to the PND)
5. Coffee (250,000 small coffee producers) will be supported. The coffee program aims at channelling productive support for an amount of 5,000 MXN (ca. 278 USD) per producer of up to 1 hectare, according to the PND)

All participants took a turn sharing their views. Sometimes the answers were more direct to the questions, however, most times, their answers pertained to generic policy needs for Mexico. Following the workshop, the authors put together a workshop report, which was distributed to the participants and read by the participants. The key findings from the workshop including the above question answers through the stakeholders' engagement process are shown in the Results and Discussion.

The grey literature survey includes the European bioeconomy strategy [48] and the European Biorefinery Outlook to 2030, “Studies on support to research and innovation policy in the area of bio-based products and services” [49]. The grey literature analyses revealed the formal bioeconomy definition as follows [48]. “The bioeconomy covers all sectors and systems that rely on biological resources (animals, plants, micro-organisms and derived biomass, including organic waste), their functions and principles. It includes and interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services (excluding medicines and health biotechnology). To be successful, the European bioeconomy needs to have sustainability and circularity at its heart. This will drive the renewal of our industries, the modernisation of our primary production systems, the protection of the environment and will enhance biodiversity.” The Mexican policy analyses and workshop outcomes have both revealed a serious lack of biorefinery and bioeconomy systems thinking, deployment and regulatory frameworks to support B4 systems in an integrated manner. Further, the European bioeconomy definition shows that despite some overlaps in the two policy landscapes between Europe and Mexico, the “interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services (excluding medicines and health biotechnology)” are needed in Mexico’s policy landscape to direct their activities with the biological resources towards a sustainable circular bioeconomy. Moreover, biorefining is an important part of a circular bioeconomy [49]. Biorefinery can address the three intersecting pressing challenges the world faces today: climate change impact, biodiversity loss and resource depletion. A biorefinery approach whereby biomass is fractionated into added-value products in a cascaded and symbiotic manner in a whole system, e.g., a country or a region, gets to tackle these challenges. Biomass is a key climate impact reduction and mitigation proposition by the way biomass captures atmospheric carbon dioxide. The value of captured carbon dioxide can be retained and enhanced by a biorefinery approach. Conserving carbon resources by biorefining and displacing fossil-based refining is an effective approach to tackle the resource depletion challenge and offer resource security. By keeping carbon in the value chain, biorefinery delivers the just transition towards a country's net-zero goals. Thus, biorefinery can deliver sustainability at the intersection of three global grand challenges, as depicted in Figure 2.

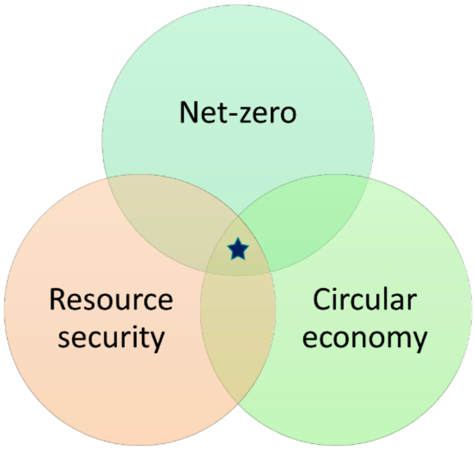

Figure 2. A biorefinery drives sustainability by delivering three intersecting strategies, net-zero, resource security and circular economy.

Biorefinery has been defined as "a facility with integrated, efficient and flexible conversion of biomass feedstocks, through a combination of physical, chemical, biochemical and thermochemical processes, into multiple products. The concept was developed by analogy to the complex crude oil refineries adopting the process engineering principles applied in their designs, such as feedstock fractionation, multiple value-added productions, process flexibility and integration" [7]. Biorefinery is a subset of a bioeconomy in the sense that the “bioeconomy covers all sectors and systems that rely on biological resources” [48]. The biorefinery is an integrated self-sustainable industrial system within the bioeconomy achieving the same goals as the bioeconomy. Biorefineries have been shown to offer the highest economic marginal value when chemicals and materials are produced. Chemicals such as nutraceuticals, pharmaceuticals, cosmeceuticals, flavors, fragrances, food ingredients, healthcare chemicals, agrochemicals, solvents and paints, etc. have several orders of magnitude higher market values compared to energy products, fuel (transport, marine and aviation), heating, cooling and electricity [7,29,37-39]. Likewise, materials such as composites, fibres (textiles, paper, board, carbon/specialty and others), organic fertilizers, polymers and resins have significantly higher market values than energy products [7,29,37-39]. Economic incentives are driving biorefinery developments towards chemical and material production in Europe and the rest of the world [49]. Thirteen chemical product groups are shown: Additives, Agrochemicals, Building blocks, Catalysts & Enzymes, Colourants, Cosmeceuticals, Flavors & Fragrances, Lubricants, Nutraceuticals, Paints & Coatings, Pharmaceuticals, Solvents, and Surfactants [49]. Composites, Fibres (textiles, paper, board, carbon/specialty and others), Organic fertilizers, Polymers and Resins are the five material groups identified [49]. The majority produce Building blocks, Pharmaceuticals, Nutraceuticals, Cosmeceuticals, Paints & Coatings, Surfactants, Flavors & Fragrances, Lubricants, and Solvents, respectively, in the chronological order of their worldwide bio-based market share. After chemicals, material products dominate, with Polymers, Fibres, Composites, Resins, and Organic fertilizers, respectively, in the chronological order of their worldwide bio-based market share. These products are produced via one-, two-, and three-platform raw material based biorefineries primarily using first-generation feedstock, twothirds of biorefineries, and only marginally using non-food biomass, municipal solid waste (MSW), lignocellulose and organic residues [49], as shown in Figure 3.

Figure 3. Biorefinery types by platforms: One-platform (top), Two-platform (middle) and Three-platform (bottom). From the left to the right, the columns represent biomass feedstock, process, platform and products.

The main biorefinery products identified include Chemicals: 1,4 butanediol (BDO), methanol and lactic acid + polylactic acid (Building block), propylene glycol (Additive), fatty alcohol ethoxylate

(Surfactant), and acetic acid (Solvent), and Materials: microfibrillated cellulose (Fibre) and lignin-based phenolic resins (Resin) [49]. Figure 3 shows the main product categories; in addition, combined heat and power (CHP) are common to generate utilizing the bottom of tonnage. As the added-value chemical products comprise <10wt% of biomass oven dry tonnage, most of the biomass feedstock is available for bulk chemical or biofuel and CHP generation [7,29,37-39]. Thus, the priority biorefinery product should be added-value chemicals before biofuel or CHP extractions, the latter will be anyway available in an integrated biorefinery system. Although Braskem (Brazil) and India Glycol (India) have been shown to convert sugarcane into ethylene/polyethylene and ethylene glycols, respectively, there is no mention of Mexico's sugarcane industries [49]. This reinstates that Mexico's sugarcane and other biomass valorization options must be recommended for biorefinery and bioeconomy policies, as shown in the following section.

3. Results

This section focuses on key findings from Mexico's current policy analyses related to B4 systems, key attributes from the workshop, and biorefinery schematics, data and evidence.

Key findings from Mexico's current policy analyses related to B4 systems: The Mexican legislation analyses show that the LTE by the SENER and PND are the primary legislative bodies to strategize bioenergy and bioeconomy systems. The main findings from the existing policy analysis are as follows.

Bioenergy-related (LTE by the SENER [47]):

1. The financing is to support rural communities that produce bioenergy, use degraded land not suitable for food crops to produce bioenergy and develop value chains.

2. Investment and financing programs including incentives will be promoted and evaluated for municipalities and the private sector that use urban waste and the recycling of materials for energy.
3. Technologies converting biomass into energy commodities are efficient wood-saving stoves, biomass drying and roasting, biodigesters to produce biogas, pelletization, gasification to produce hydrogen and biotechnological, enzymatic and algal routes to biofuels.
4. Rural solid wastes including those used for biogas generation are a way to alleviate the energy poverty of the communities.
5. Clean electricity from biomass will be supported for small, isolated communities, totalling some two million inhabitants, which lack electricity access.
6. Non-food bioenergy including biofuel systems and their economic and environmental impact assessment including LCA capabilities will be promoted.
7. Bioenergy includes electricity, heat, cooking fuel or biofuel generation from biomass.
8. Technical capabilities and human resources are to develop training programs in planning and financing of processes and operation of more advanced technologies for pre-treatment, production, improvement and use of bioenergy.
9. Actions include increasing investment certainty, establishing technical standards and sustainability criteria, developing and implementing a national sustainable land use management system that promotes balanced and sustainable use of agricultural and forest land.

Bioeconomy-related (PND [45])

1. Agroecological and sustainable practices, soil conservation, water and agro-diversity among producers will be supported

2. Self-sufficiency in producing seeds and other inputs, as well as machinery and equipment appropriate to small-scale agriculture, and implementing renewable energy systems are encouraged.
3. The renewal of coffee plantations, the use of better genetic materials, the implementation of sustainable production practices, the addition of value and differentiation of their products, the conservation and better use of soil and water and the conservation of biodiversity are being supported.
4. The same as in number 3. applies to sugarcane plantations in the country.
5. There is the acquisition of agri-food products at guaranteed prices.
6. There are distributions of fertilizers, improved seeds or any other products that contribute to raising the productivity of the field.
7. The industrialization of basic foods, milk and its derivatives, as well as the commercialization of surpluses from agri-food production inside and outside the country will be supported
8. Micro, small and medium private companies associated with the commercialization of food products will be created and promoted.
9. Scientific research and technological development will be supported and the basic basket in regions of high economic marginalization will be distributed.

From the analyses of PND and LTE, it can be observed that biodiversity, circular economy, whole system approaches and biorefineries which convert bio-based wastes and residues into added-value chemical, material and bioenergy products are neglected [45,47], while biodiversity, circular economy, whole system approaches and biorefineries are imperative in Europe’s bioeconomy strategies [48,49]. Figure 4 shows the resulting overlap and distinction between PND, LTE and “Transition

Strategy to Promote the Use of Cleaner Technologies and Fuels" (Energy Transition Law, LTE) by the Ministry of Energy (SENER) provide bioenergy-related actions the new bioeconomy policy for Mexico.

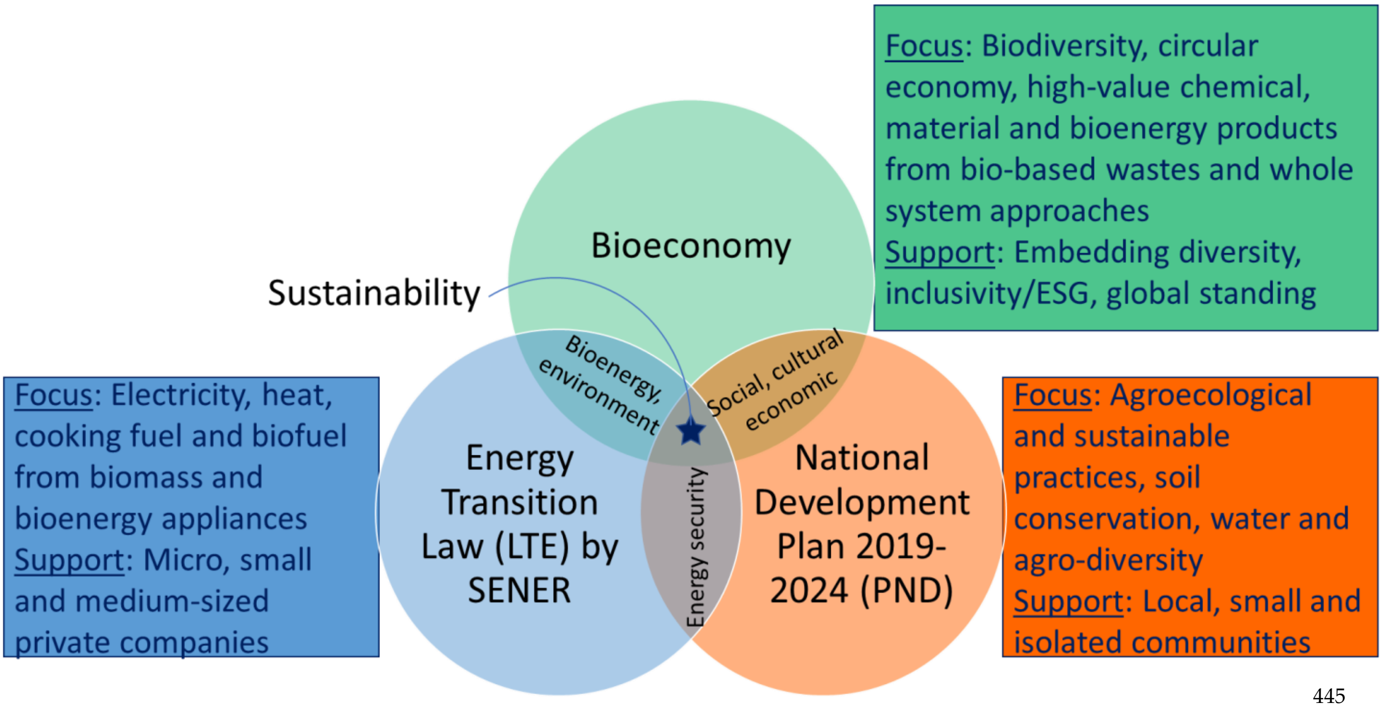

Figure 4. PND, LTE and the recommendation for a new bioeconomy policy for Mexico.

Incorporating a bioeconomy policy for Mexico will create an overlap between the new bioeconomy policy and PND by offering social, cultural and economic benefits to the country. The overlap between PND and LTE can achieve energy security. Embracing the bioeconomy will offer bioenergy and environmental benefits at the overlap between LTE and a new bioeconomy policy for Mexico. The new bioeconomy policy will support diversity, inclusivity (environmental, social and governance, ESG), and global competitiveness for the country. As the bioeconomy by means of biorefining can keep a fine balance between the ecosystem and society, we see significant upliftment opportunities for poor marginal communities through local livelihoods, entrepreneurship, and education in the country. Bioeconomy inheriting circular economy at the core of the activities will underpin resource security and net zero for the country (Figure 2). At the intersection of PND, LTE and the new recommended bioeconomy policy, sustainability or the UN SDGs can be achieved in Mexico. Thus, Mexico's B4 systems-related policy analyses have helped to make a complementary bioeconomy policy recommendation for Mexico.

Key findings from the workshop: The main findings from the workshop are as follows. Further, the framework in Figure 4 is confirmed at the workshop with the workshop participants.

1. For a bioenergy system to be more economically viable there is a need to make it flexible through by-product generation and multi-feedstock biorefineries.
2. Incentives are needed to enable the conversion of 2 million tonnes per annum of sugarcane excess for bioethanol and other bioproducts
3. Policies for biofuel introduction through blending mandates or incentives are needed
4. There is a need to base decisions based on whole life cycle assessments
5. Air pollution other than CO_2 emissions needs to be considered in designing policies for introducing bioethanol, according to atmospheric conditions of cities such as Mexico City
6. Policy for electricity generation threshold in self-consuming enterprises needs to be revised to enable larger capacities where biomass feedstock is available and thus extended benefits to communities

Furthermore, the question answers from the stakeholders' discussions are assimilated as follows.

1. It was commented that the biofuel blending mandate in Mexico is still to be put into practice and it is pending approval for introduction in large cities. There were some projects in the past to produce bioethanol. Most sugars extracted are either exported to the USA or turned into consumable alcohol. Mexico is 7th largest sugar exporter in the world.

An important remark by Mexico City’s government representative is that more research and scientific basis and life cycle approaches are needed to support the introduction of bioethanol. Concerns are on volatile emissions that may generate health and air pollution issues in the city. This should be considered in policymaking and approval of mandates in Mexico to prevent these environmental issues but also health problems.

2. It was commented that for a bioenergy system to be economically feasible there is a need to make them flexible through by-product generation and multi-feedstock biorefineries. There are variations in composition and availabilities with seasons, which need to be considered to advance TRL as well.
3. It was commented on many times that just doing it is the best strategy if it makes economic sense for companies, organisations or communities implementing a bioenergy project and within regulatory constraints. Thus, a financial investor push is also a key ingredient for the energy transition.

The case of a wood mill with 1 MW generation capacity was discussed as an example of policy changes needed. In a scheme of self-consumption generation with the current policy and regulatory framework, the mill is currently allowed to generate 0.5 MW [3]. Distributed Generation is Ruled by Article 68 of LIE, it is an option with a power limitation of 0.5 MW, and it is a classic "net metering" option where the industrial park is still supplied by a third party (Qualified Supplier or Basic Supplier), but such main input is completed by additional distributed generation installation. As such, a "compensation agreement" is entered between the industrial park or warehouse as the final user and the operator of the distribution or transmission grid – that is, the Mexican Federal Electricity Commission (Comisión Federal de

Electricidad, or CFE) [50-52]. However, there is potential to generate more and create a higher impact on communities and local governments if the policy is changed [3]. This will impact the implementation of similar facilities in the forestry industry which is also becoming a key bioenergy player in Mexico. The policy seems to be a needed driver to promote bioenergy generation and replicate this successful case study [3].

4. Sugarcane bagasse is a lignocellulosic biomass and the major source contributing to bioenergy generation in Mexico due to the large amounts produced in sugar mills. This has contributed to renewable energy goals and climate change mitigation in this industry. As such this and other similar agroindustries are key players in the energy transition and energy security in Mexico, which directly impacts the farmers and local communities. However, burning biomass can have other issues such as generating particulate matter and ash which are important parameters discussed by environmental regulatory agencies.

   The potential of about 2 million tonnes of sugar that are produced annually in excess by the country was discussed. This sugar is sold in the international market at low prices which is not attractive for sugar mills. It is proposed to produce bioethanol from the available sugar or sugarcane juice. Ethanol can be a fuel to blend with gasoline or a building block chemical used to make ethylene/polyethylene (Braskem, Brazil) and ethylene glycols (India Glycol, India) [49]. However, there are policy needs to support this shift and required investments to retrofit sugar mills into biorefineries for bioethanol and other products for national markets.

5. Some examples of how knowledge exchange and awareness for the local population are needed. Some farmers, for example, are not interested in collecting and selling biomass because they don’t see many benefits from that or are comfortable with current activities, wages

and social aid income. Furthermore, to complement the policy and workshop attributes, literature-based coffee waste biorefining potentials are shown in the following section.

Biorefinery schematics, data and evidence: It is evident from the policy and workshop outcome analyses that a new bioeconomy policy is imperative to achieve sustainability, resource security, net zero and a circular economy in Mexico (Figures 2 and 4). Biorefinery offers a way to achieve an inherently circular bioeconomy [7]. Both the policy and workshop outcome analyses have revealed the main gaps, no clear indication of bio-based added-value products (chemicals and materials) from biomass to support local livelihoods, entrepreneurship and education, policy shifts to support required inward investments to retrofit bioenergy systems or sugar mills into biorefinery systems and pollution control and mitigation by diverting pollutants into value-added resources.

Following the formal definition of biorefinery, “a facility with integrated, efficient and flexible conversion of biomass feedstocks, through a combination of physical, chemical, biochemical and thermochemical processes, into multiple products” [7], we provide priority biorefinery configurations and specifications. These will be suitable to transform an existing facility into a biorefinery facility to deliver the benefits of the bioeconomy.

Sustainable biomass feedstocks are non-food unavoidable waste bioresources [53], which can be classified into four categories, as shown in Figure 5. Depending on the biomass types, their production options are shown. This is a simpler and more adaptable biorefinery selection framework compared to Europe’s biorefining strategies [48,49] because of the simpler categorization by feedstock types rather than platform types which could be too many. Lignocelluloses are agricultural, forestry, grassland and garden wastes and residues [7,54]. The extraction of ethanol from lignocelluloses involves the fermentation of sugar extracted from celluloses and hemicelluloses after lignocellulose decomposition leaving an insoluble black liquor containing lignin [55,56,57]. Biodiesel or sustainable aviation fuel is produced by esterification/transesterification of oily wastes [34,35] or hydrodeoxygenation [54,58,59]. Microalgae can be esterified/transesterified into biodiesel [7], while macroalgae undergo separation and chemical conversions to make high-value chemicals [29]. Organics present in wastewater can be anaerobically digested into biogas [60], while pollutants present in wastewater can be recovered as resources using microbial electrosynthesis [39].

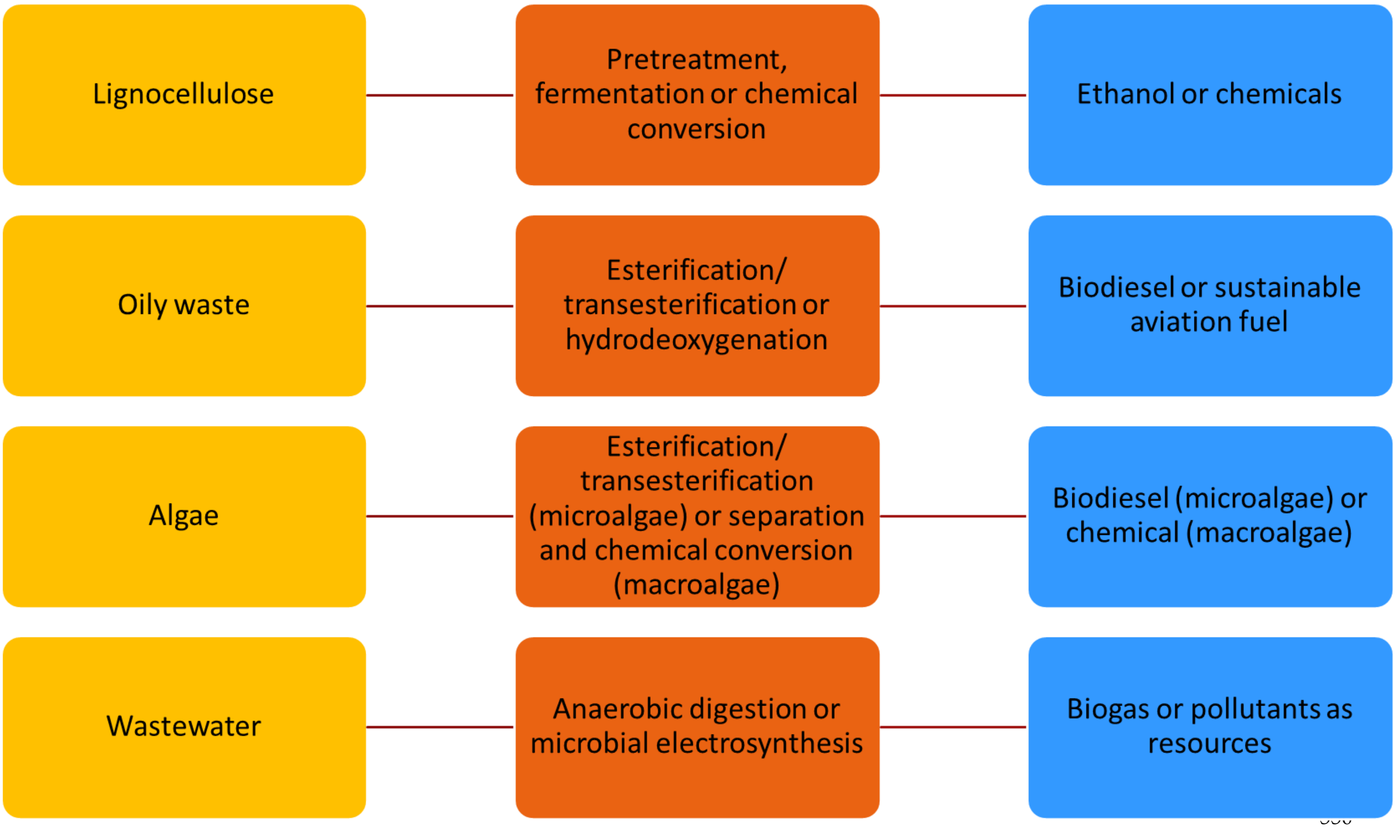

Figure 5. Biorefinery classification by waste biomass feedstock type. The columns from the left to the right indicate biomass, process and products.

We further elaborate the non-exclusive biorefinery configurations given their relevance in the bioeconomy transition for Mexico. Figures 6-8 show the standard biorefinery schematics to convert biomass into bioethanol, biodiesel and renewable fuels. Figures 9-10 show the chemical production options from biomass via C5 and C6 sugar and lignin platforms [7], and via polysaccharide and protein platforms [29], which can attract inward investments given the richness of biomass availability in

Mexico. In addition, a gasification-based superstructure is shown in Figure 11, given its infrastructure compatibility and syngas being an important platform [7].

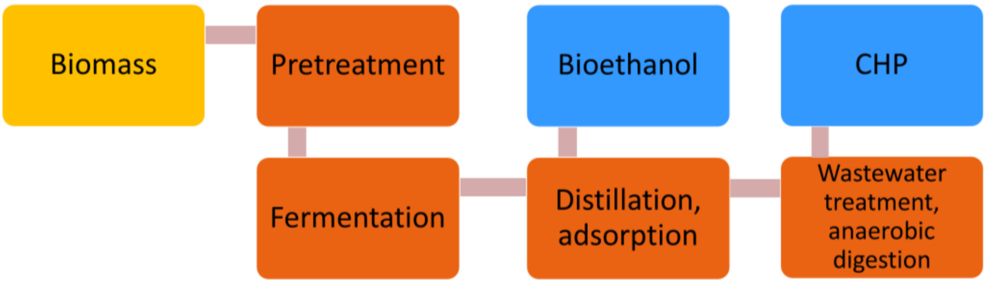

Figure 6. Biomass via pretreatment, fermentation, separation, wastewater treatment, anaerobic digestion and CHP to ethanol production.

Given the massive importance of ethanol in Mexico [25,32,33,41,55], and 2 million tonnes per annum of excess sugarcane availability in Mexico [61], as shown in the workshop outcome, a straightforward approach is to produce ethanol from sugar or sugar juice extracted from sugarcane. This is in line with what was observed in the workshop: one of the answers to Q3: “Just doing it is the best strategy if it makes economic sense for companies, organisations or communities implementing a bioenergy project and within regulatory constraints. Thus, a financial investor push is also a key ingredient for the energy transition.” From the sugar mills’ or sugarcane industries’ current configurations, additional investments will be required to produce pure ethanol. This will comprise investments for the downstream separation and energy recovery processes including adsorption, wastewater treatment, anaerobic digestion and CHP. The latter three steps could be shared facilities with adjacent industrial systems (industrial symbiosis). CHP is needed for the self-sustainability of the bioethanol-producing biorefinery [55,56,57]. It has been shown that with increased sugar content in the biomass feedstock, ethanol production increases, making the plant starve for electricity and heat, which can be generated on-site using lignin, tar and biogas recovered from anaerobic digestion. As expected, Figure 5, although does not explicitly show the low-value options, CHP and animal feed, they are often the co-products of the biorefinery systems.

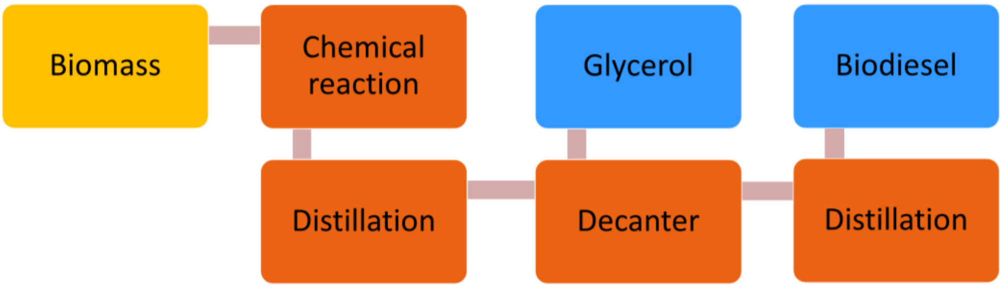

Figure 7. Biomass via esterification/transesterification and separation to biodiesel production.

Biodiesel is an important biofuel alternative to diesel. Biodiesel can be blended with petroleum-derived diesel. Biodiesel can offer energy and economic security to developing nations if produced locally from indigenous biomass. Its application is as fuel: automotive, marine, agriculture and power generation. Anhydrous biodiesel production is feasible from used cooking oil. This is a sustainable way to run diesel vehicles. Mexico has a plethora of first-generation feedstocks such as vegetable oils: canola, palm, soybean, corn, etc. suitable for biodiesel production. Waste oils and fats are alternative feedstocks. Algae are another feasible feedstock. The co-production of high-quality glycerol or glycerol-derived chemicals, with biodiesel as the main product where possible is recommended to maximize resource efficiency [7]. An industrial process must not stop at the reactor stage. The process must include a fractionator for methanol recovery/recycling to the reactor, a decanter to recover glycerol and a fractionator to purify biodiesel from the residual stream [62]. In addition, a heat recovery network should be synthesized considering pinch analysis [7]. Demands for heating, cooling and electricity for driving fluids around the process must be met by on-site CHP generation using the various organic-containing streams in the process. Research has primarily focused on the novel catalyst or catalytic reactor for converting triglycerides into fatty acid methyl esters (FAME) known as biodiesel. Whole process and system considerations are important for sustainable development, e.g., analyzing the life cycle environmental impacts due to land use and land use change to grow oily crops.

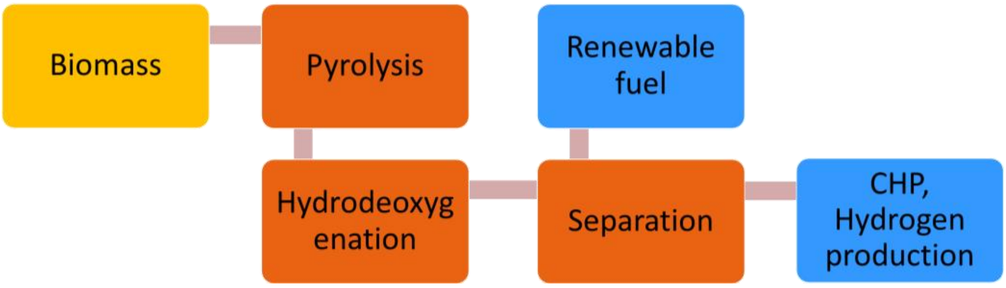

Figure 8. Biomass via pyrolysis, hydrodeoxygenation, separation, CHP and hydrogen generation to renewable fuel production.

A self-sustainable renewable fuel producing biorefinery comprises 1) pyrolysis of biomass into gas, bio-oil and char, 2) bio-oil hydrodeoxygenation and hydrocracking producing renewable fuel of middle distillate quality and small chain alkanes, 3) alkane steam reforming and pressure swing adsorption (PSA) producing green hydrogen and carbon monoxide; 4) mixed ionic electronic conducting membrane (MIEC) splitting high pressure superheated steam (HPSS) into green hydrogen and oxygen, and 5) CHP using pyrolysis gas and carbon monoxide from PSA as fuel with oxygen from MIEC, to fulfil the demand for HPSS and electricity [54]. The process is highly compatible to integrate to crude oil refineries [7,54,59] such as Pemex. The infrastructure compatibility is due to many common units, hydrocracking, distillation trains, CHP, PSA, etc. [7,54,59]. Biomass, thus, can be co-processed to directly produce blended middle distillate grade products that will be partially bio-based [7,54,59].

Biofuels have been shown to benefit the agricultural sector in the following ways, (1) promoting a shift from wasteful annual crops to perennials, particularly low-input high-diversity crops; (2) sequestering carbon in soil both organically and as biochar; (3) improving conservative water management practices; and (4) recycling resources [17]. In Mexico, bioethanol and biodiesel production can be supported by an incentivized or mandated blend with fossil-derived transport fuel counterparts

[41]. The financing is to support rural communities that produce bioenergy, favoring the use of degraded land not suitable for food crops, facilitate access to financing for the production of sustainable bioenergy that favors the development of value chains, promote the investment necessary to attract biofuels to the market and evaluate the establishment of financing programs or incentives for municipalities and the private sector that use urban waste for energy [47]. The biorefining strategies in Figures 6-8 are in line with efficient technologies such as biodigesters to produce biogas, gasification, biotechnological, enzymatic and algal routes to biofuels, supported by the LTE [47]. Biofuel production rather than burning biomass can mitigate other issues such as generating particulate matter and ash which are important parameters discussed by environmental regulatory agencies at the workshop. For a bioeconomy, chemicals such as Building blocks, Pharmaceuticals, Nutraceuticals, Cosmeceuticals, Paints & Coatings, Surfactants, Flavors & Fragrances, Lubricants, and Solvents, etc. need to be the main products of biorefinery, which are the focus of Europe’s 2030 biorefinery outlook [49]. There may be food, feed and energy co-productions, however, they are not the economic drivers of most biorefineries worldwide. Thus, a country like Mexico, which is rich in bio-based resources, can make a step change in the bioeconomy by providing bio-based chemicals and thereby become exemplary for the rest of the world. Europe’s 2030 biorefinery outlook lists 120 bio-derived chemicals. Here, we show the top 40+ chemicals [7] via the C5 and C6 sugar, lignin and microfibril platforms (Figure 9). Another form of chemical biorefinery, which is also distinctive in Europe’s 2030 biorefinery outlook [49], comprises polysaccharide and protein platforms (Figure 10) [29]. These biorefineries are recommended to offer a competitive edge for a biomass-rich country like Mexico over Europe and the rest of the world. Although most chemical production routes are well known, their deployments via chemical biorefineries will be novel.

Gasification has been a significant process for thermochemical-based biorefining and producing syngas as an important platform [7]. Syngas has been recognized as a platform in Europe's 2030 biorefinery outlook [49]. Gasification was first integrated into crude oil refineries to convert the bottom of the barrel into syngas as a clean energy carrier [63,64,65]. Biomass, typically lignocellulose, was then gasified, the gas product was cooled to recover heat into high pressure superheated steam generation and cleaned, and the syngas thus produced is combusted into a combined heat and power generation – the integrated schematic is known as biomass integrated gasification combined cycle [66]. Furthermore, syngas integration with high temperature solid oxide fuel cells is shown to enhance the energy efficiency of the biomass integrated gasification fuel cell system [66,67,68,69]. Beyond energy, gasification was further integrated to produce/recover hydrogen from syngas in a hydrodeoxygenation-based process to produce green diesel [58]. Biomass gasification has been the key process to producing methanol as an important chemical or Fischer-Tropsch fuel [70,71], later on, which features in the European 2030 biorefinery outlook [49]. Another important aspect of gasification is that the resulting carbon dioxide, pre- or post- combustion is capture-ready [8] as well as can be used to produce chemicals further (carbon dioxide utilization, CDU and carbon dioxide capture utilization storage, CCUS) [72]. These remarkable uses of gasification make it a worthwhile recommendation in Mexico's bioeconomy policy. Moreover, gasification has attracted a mention in LTE [47]. Combining the above integration opportunities, a biomass gasification-based superstructure is shown in Figure 11.

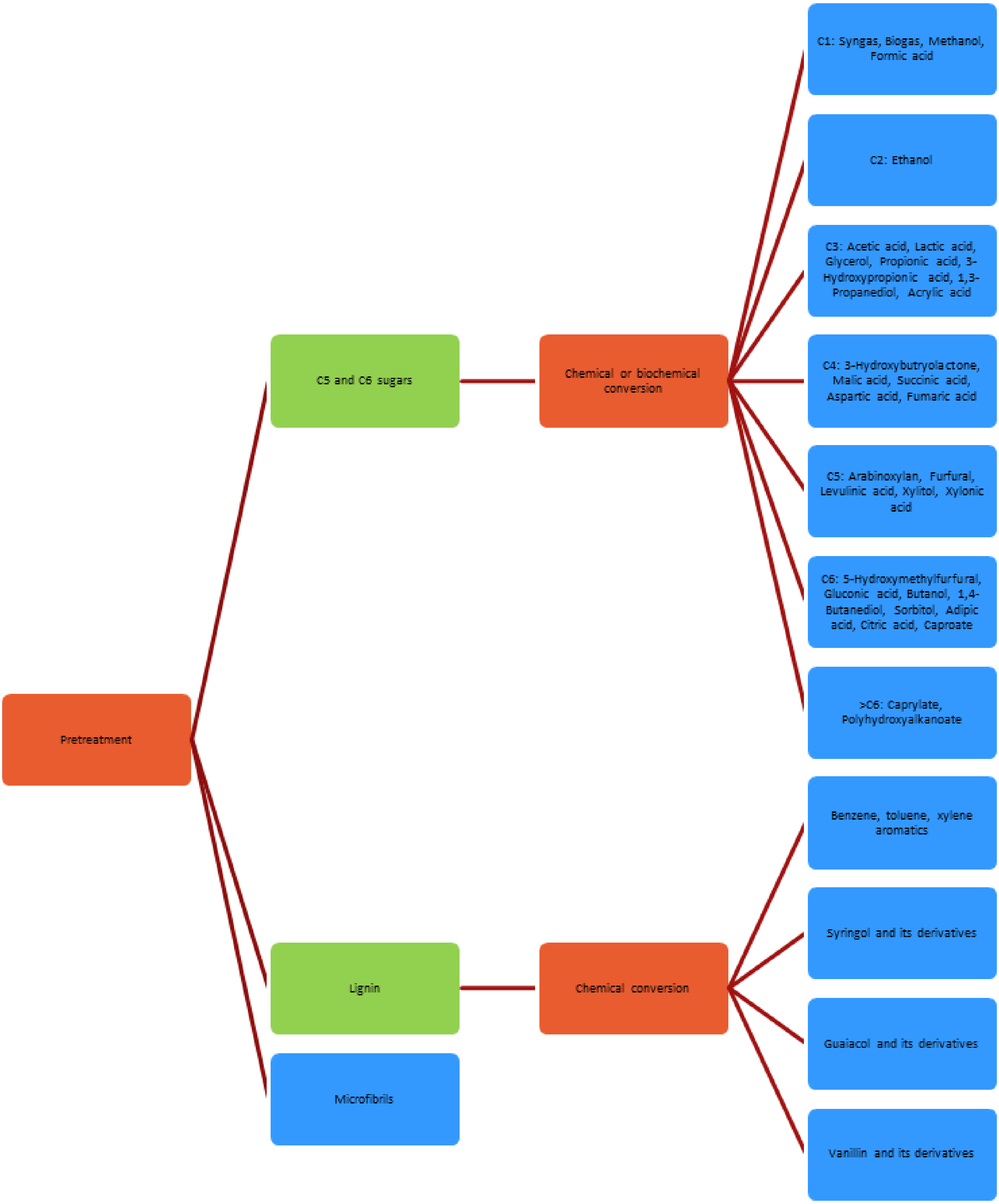

Figure 9. Biomass via pretreatment and chemical or biochemical conversions to chemical products.

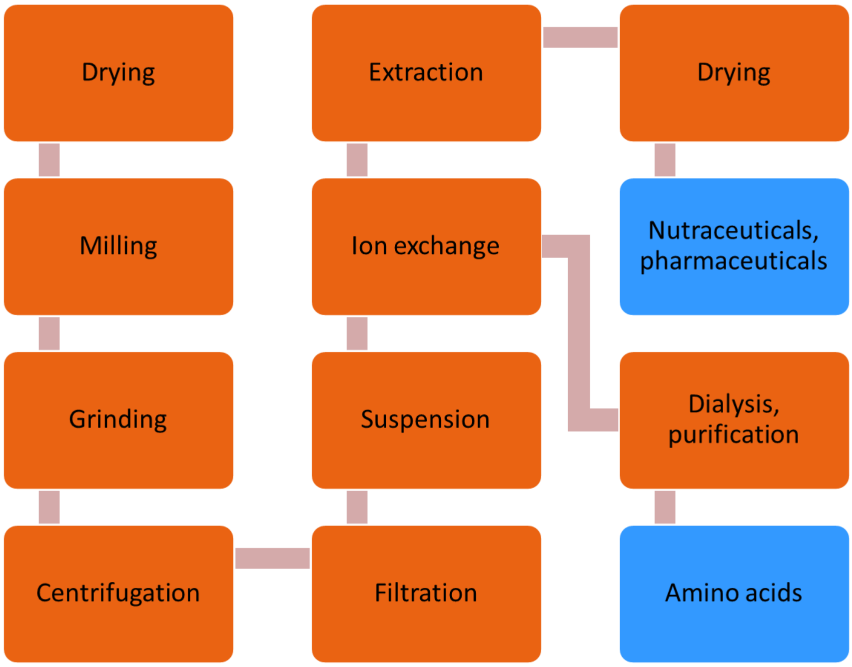

Figure 10. Biomass via extraction/separation steps to polysaccharide-derivatives, i.e., nutraceuticals and pharmaceuticals, and protein-derivatives, i.e., amino acids.

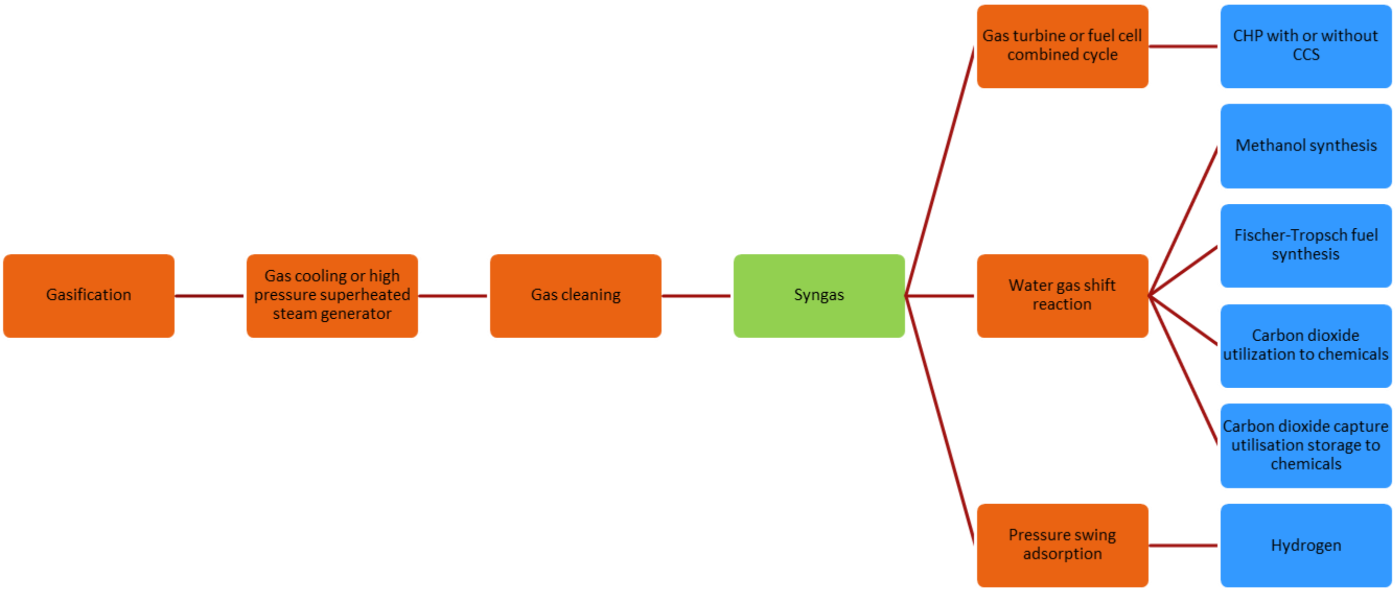

Figure 11. Biomass gasification-based superstructure to utilize syngas as a platform to produce a variety of products, chemicals, hydrogen, fuels, and CHP (also with or without CCS).

Table 1 shows the conditions and life cycle GHG impacts of the schematics in Figures 6-11 for their relevance and recommendations for Mexico's new bioeconomy policy.

Table 1. Specifications, yield and environmental drivers of biorefineries converting biomass into products.

Product	Feedstock specifications	Yield	GWP saving	Fossil resource saving	Reference
Ethanol (Figure 6)	Biomass wet analyses Moisture: 25wt% Cellulose: 30wt% Hemicellulose: 28wt% Lignin: 15 wt%	Ethanol: 0.18 wt/wt biomass Electricity: 80 kWh/t biomass Nutrient: 0.11 wt/wt biomass	0.6 kg CO_2e/kg ethanol	50 MJ/kg ethanol	[70]
Biodiesel (Figure 7)	Oily feedstock content Triglyceride: 50wt% Free fatty acid: 50wt%	Biodiesel: 0.95 wt/wt biomass Glycerol: 0.05 wt/wt biomass	2.8 kg CO_2e/kg biodiesel	35 MJ/kg biodiesel	[58]
Renewable fuel (Figure 8)	Bio-oil composition	Fuel: 0.34 wt/wt biomass Char: 0.12 wt/wt biomass	2.8 kg CO_2e/kg fuel	37 MJ/kg fuel	[51,59]
Chemicals (Figure 9)	Biomass dry analyses Cellulose: 20wt% Hemicellulose: 50wt%	Succinic acid: 0.52 wt/wt biomass Lactic acid: 0.65 wt/wt biomass 2,5-Furandicarboxylic acid (FDCA): 0.45 wt/wt biomass	1.9 kg CO_2e/kg succinic acid 2.2 kg CO_2e/kg lactic acid 2.5 kg CO_2e/kg FDCA	27 MJ/kg succinic acid 37 MJ/kg lactic acid 36 MJ/kg FDCA	[29,71]
Nutraceuticals Pharmaceuticals Amino acids (Figure 10)	Biomass dry analyses Cellulose: 20wt% Hemicellulose: 50wt% Protein: 10wt%	Nutraceuticals: <10wt% biomass Pharmaceuticals: <10wt% biomass Amino acids: <10wt% biomass	3 kg CO_2e/kg nutraceuticals 3 kg CO_2e/kg pharmaceuticals 13 kg CO_2e/kg amino acids		[29]
Levulinic acid	MSW analyses	Levulinic acid: 0.07 wt/wt MSW	2.4 kg CO_2e/kg levulinic acid	60 MJ/kg levulinic acid	[37]
Methanol (Figure 11)	Biomass ultimate analyses	Methanol: 0.4 wt/wt biomass or 0.58 wt/wt bio-oil	40% reduction		[49,67]
Hydrogen (Figure 11)	Biomass ultimate analysis C: 37wt% H: 5wt% O: 41wt%	Hydrogen: 10 wt/wt%	22 kg CO_2 eq./kg hydrogen	4 kg/kg hydrogen	[63]

The ethanol production process in Table 1 utilizes lignocellulose materials, which are agricultural, forestry and garden wastes, which can be seen from the feedstock analysis. Most ethanol production processes, however, rely on first-generation or human-consumable food, sugarcane (Brazil), corn (USA) and sugar beet (EU), rather than their residues, sugarcane bagasse, corn stover and sugar beet pulp. Using first-generation feedstock has negative ecological consequences on land use and land use change, including deforestation and biodiversity loss, while the residue or waste biomass suffers from lower yields because of the lower amount of extractable sugars. In addition, the on-site enzyme production and utilization have been considered for the results in Table 1. The enzyme production also consumed some extracted sugars. The yield of ethanol is 18% of the weight of biomass for its given composition [73]. The online open-access platform allows for examining the techno-economic and environmental sustainability of the process with changing user inputs such as biomass composition [73]. The process is still economically viable due self-generation of CHP, which is directly proportional to the amount of lignin present in biomass as lignin is the main fuel for the CHP. Each kilogram of bioethanol could save 0.6 kg CO_2e and 50 MJ of primary fossil energy by substituting petroleum-derived gasoline. The mathematical correlations and parameters for the process simulation and evaluation are detailed elsewhere [55]. It is prominent that ethanol production from sugarcane to blend with gasoline to reduce climate change impact and emissions is a priority in Mexico, which can be achieved by mandated blending requirements, of 5-10% by energy to begin with. Sugarcane bagasse is used for CHP generation. Excess energy available is transformed into electricity to export. Sugarcane growers can thus benefit from the revenue generated from ethanol and electricity production and such projects can embrace socio-economic equity in the short term. In the longer-term, two things a country can do: i) move to lignocellulosic feedstock thereby relieving the land for forestation and thus CO_2 sequestration; ii) produce ethanol as a precursor to added-value products, such as polyethylene like Braskem, Brazil and mono ethylene glycol as the monomers to polymers; or an advanced sustainable jet fuel obtained through the alcohol-to-jet (ATJ) process.

Biodiesel is produced from oily feedstocks. Waste cooking oils, oily residues and wastes are non-food non-consumable biomass that can be converted into biodiesel. The production process of biodiesel from oily feedstock and microalgae is well established [7,34,35]. Anhydrous biodiesel yield from dry waste oils or oily residues is high and so is the saving in global warming and fossil resource depletion potentials [62]. The online open-access platform allows for examining the techno-economic and environmental sustainability of the process with changing user inputs such as oily feedstock composition [62]. Biodiesel being a viable fuel for automotive, marine, agriculture and power generation applications could be relevant for Mexico. Jatropha has been explored for biodiesel or green diesel (via hydrodeoxygenation) production in Mexico [58].

Renewable fuel, middle distillate, kerosene or jet fuel or sustainable aviation fuel can be produced from oily wastes or residues or lignocelluloses via hydrodeoxygenation. The detailed process integration, simulation and evaluations are shown elsewhere [54]. In-process hydrogen and CHP generation to make renewable fuel holds the promise for sustainability, e.g., achieving significant global warming potential and fossil resource depletion potential savings [54]. Given the infrastructure compatibility, e.g., hydroprocessing, distillation, pressure swing adsorption, CHP, etc. could be shared units between a refinery and a biorefinery, the process (Figure 8) is best suited adjacent to a crude oil refinery, however, this would make the logistics of already challenging logistics of biomass harder.

Given the versatility of the chemical product options from a biorefinery, we prioritize the chemicals that show promise in reducing climate change impact potential by the substitution of fossil-based counterparts. These chemicals are among the chemicals produced in Europe and the rest of the world [49]. The greenhouse gas emission reduction potential of their production is also supported by comprehensive life cycle assessments [7,29,37,74]. 2,5-Furandicarboxylic acid (FDCA), lactic acid and succinic acid are produced by the fermentation of sugars extracted from celluloses and hemicelluloses of lignocelluloses, while levulinic acid is produced by controlled acid hydrolysis of sugars extracted from celluloses [7,29,37]. In biorefineries, these products are extracted alongside other co-products and thus, the total life cycle global warming potential impact is shared between the products. This allocation could be done based on mass distributions [29] if the products have similar economic values or by their market prices [37]. If the mass yield is low such as in the case of levulinic acid extracted only from celluloses, but not hemicelluloses, by acid hydrolysis, the mass allocation gives a very high global warming potential. Economic allocation then does skew the chemical's allocated global warming potential. The saving in global warming potential is calculated by subtracting the chemical's allocated global warming potential from the biorefinery producing it from the global warming potential of its counterpart production from fossil resources. These chemicals have numerous derivatives: Pharmaceutical>Specialty chemical>Solvent>Fuel and additive from high to low value products, respectively [7]. In addition, amino acids can be extracted via protein isolation from protein-rich biomass, such as seaweed or macroalgae [29]. When proteins and carbohydrate derivatives (nutraceuticals and pharmaceuticals) are co-produced (Figure 10), global warming potential savings and economic margins are amongst the highest among biorefinery options [29]. Methanol is a platform chemical produced by conditioning the syngas from biomass gasification adjusted to achieve a hydrogen-to-carbon monoxide molar ratio of ~2 [70] curbing the global warming potential by 40% by substituting methanol from fossil resources [49]. Hydrogen production from biomass gasification, gas cooling, cleaning and conditioning, followed by pressure-swing adsorption (Figure 11) is environmentally sustainable.

Leading examples of industrial-scale biorefining [49] are shown highlighting their main characteristics, continuous innovation, diversifying biomass and product, and securing and expanding resources in an integrated manner following the bioeconomy philosophy.

Sugar or starch-based: Sudzucker AG & CropEnergies produce ethanol via the fermentation of carbohydrate-containing biomass, such as sugar or starch and has the flexibility to process sugar beet, wheat, maize and barley. It co-produces animal feed and CHP. Excess CHP is exported. They also produce food-grade carbon dioxide. Alongside, neutral alcohol is produced for the beverage, food, cosmetics and pharmaceutical industries. Braskem produces ethanol from sugarcane, while bagasse is used to produce CHP for the site and excess to export. Ethanol makes polyethylene (low-density, linear low-density and high-density), making Braskem the largest exporter of bio-based polyethylene. Their Sugarlite contains 40% bio-based content from Braskem's sustainably sourced I'm green^{TM} (polyethylene), which makes ethylene vinyl acetate to make Native Shoes. India Glycol, India also ferments sugarcane to make ethanol that is transformed after a series of catalytic chemical conversions into monoethylene glycol as the main product, but also some diethylene glycol and triethylene glycol as co-products. India Glycol specializes in green technology-based chemicals and claims to be the world’s largest maker of ‘green ethylene oxide’, which is the intermediate from bioethanol to monoethylene glycol. It contributes to the bio-ethylene oxide derivative business, including a multi-purpose production facility with an alkoxylation plant. It also has secured sugar-based food or nutraceutical products to secure resources and diversify products. Furthermore, monoethylene glycol is reacted with terephthalic acid to make a partial bio-based polymer, polyethylene terephthalate, which makes up partially the bio-based plastic bottles for Coca Cola and Danone. Ethylene glycol is a useful industrial compound found in many consumer products. Examples include antifreeze, hydraulic brake fluids, some stamp pad inks, ballpoint pens, solvents, paints, plastics, films, and cosmetics. It can also be a pharmaceutical vehicle. Corbion and Total-Corbion are engaged in lactide monomer and polylactic acid (PLA) production (for the bio-based plastic bottles) utilizing sugarcane, first by C6 sugar extraction and then by sugar fermentation producing lactic acid followed by chemical conversion and separation [7,29]. Cosun uses a wide range of sugar and starch-based biomass to extract multiple added-value products, micro-fibres, arabinoxylans and galacturonic acid [see arabinoxylan extraction processes: 75-77]. Its products range from cosmetics or bio-based ingredients through food and food ingredients to fuel and animal feed. Covestro ferments raw sugar to produce a precursor that is chemically transformed into aniline as a building block chemical for a variety of products, polyurethane foam, agricultural chemicals, synthetic dyes, antioxidants, stabilizers for the rubber industry, herbicides, varnishes and explosives. One of Cargill's primary products is high-quality sweeteners (sorbitol) from corn or wheat. Cargill + Natureworks, Blaire, USA ferment sugars extracted from corn into ethanol and lactic acid (Cargill); lactic acid is then converted into polylactic acid (Natureworks); corn oil and animal feed are other products. Roquette, Lestrem, France utilizes wheat and corn to extract and isolate native and modified starches, polyols, proteins, sweeteners, specialty food/feed products and pharmaceutical ingredients. Novamont, Terni, Italy uses local resources including starch crops to create biodegradable and compostable starch polymers (Mater-Bi), lubricants and biodegradable greases (Metrol-Bi) and cosmeceuticals (Celus-Bi). Novamont, Adria, Italy ferments sugars extracted from corn to produce 1,4-butanediol. It is mainly used to produce other organic chemicals, particularly the solvent oxolane (also known as tetrahydrofuran). It has a role as a neurotoxin, a protic solvent and a prodrug. Bioamber, France ferments crop (e.g., corn) derived glucose to produce succinic acid.

Woody resource-based: Lenzing, Austria uses beech wood in the sulphite pulping process to extract various brands of textile applications. The spent liquor is extracted into acetic acid and furfural by vapor condensation. With Dupont/Danisco, they further extract xylose as a sweetener. Residual liquor is fuel for the CHP generation. Borregaard, Norway converts spruce wood and wood chips through innovative biorefining into specialty cellulose, microfibrillated cellulose, lignosulfonates, vanillin, ethanol, acetic acid and CHP. Lignin-value extraction has been established in the literature [7]. Using wood (Aspen, poplar, spruce and pine), Alberta Pacific Forest Industries, Canada converts a stream from their Kraft pulping process into methanol and CHP [70]. Bio-methanol is a versatile ingredient that can be used to manufacture items such as plastics, solvents, dyes, glues, polyester and other high-value products. There are a handful of pulping processes with tall oil and other byproducts recovery.

Lignocellulosic (forestry and agricultural waste) biorefinery: Clariant developed an exemplary bio-ethanol plant coproducing biogas and CHP using the proven configuration [55,56]. Clariant sunliquid® plant is built on a 10-hectare area, in Podari, Dolj County and has an annual production capacity of 50,000 tons of cellulosic ethanol from the processing of 250,000 tons of straws, thus resulting in a yield of 20wt% close to the value (18wt%) shown in Table 1 [55,73]. The agricultural residues used as raw materials are sourced from local farmers, who become part of the supply chain, with long-term benefits for the development of sustainable agriculture. The cellulosic ethanol produced using the innovative sunliquid® technology, from agricultural residues such as wheat straw, is an advanced, sustainable and carbon-neutral biofuel. It can be used on the existing car infrastructure and is part of the European Union's pollution control regulations. The plant in Podari is creating new jobs as well as business opportunities that will bring economic growth potential to this rural area. Through this investment, Clariant shows that the commercial production of cellulosic ethanol based on sunliquid® technology is both technically and economically viable, with tangible long-term benefits. Avantium, Netherlands produces monoethylene glycol, 2,5-furandicarboxylic acid and lactic acid from extracted sugars. Its YXY® Technology catalytically converts plant-based and lignocellulosic-extracted sugars into FDCA, the main building block of PEF (polyethylene furanoate), a 100% plant-based, fully recyclable plastic material with significant performance benefits and with a significantly lower carbon footprint than fossil-based plastics [78]. PEF-made packaging, film and textiles have a market share of 150, 80 and 40 billion USD [78]. There are some pilot-scale explorations [49] showing the versatility and expansion potential as follows. Lactic acid is also the product of choice for Cellulac, Ireland, from lignocellulosic biomass via pretreatment and fermentation [7]. Used as a food preservative, curing agent, flavoring agent and an ingredient in processed foods used during meat processing, lactic acid is the key ingredient in the plastics they produce. Following isolation, depolymerization and fractionation, lignin is converted into aromatics in Biorizon LignoValue. Methanol and dimethyl ether are produced via the gasification route from wheat straw by Karlruhe Institute of Technology, Germany. Pyrolysis oil and CHP are produced from wood chips by Empryro, the Netherlands and sawdust by Lieksa, Green Fuel Nordic Oy, Finland [7].

Natural fibre-based: Natural fibre composite (Ecotechnilin, France and Poland), hemp bioplastics (Kanesis, Italy) and biomaterials (fibre for industrial applications, insulation, composites), oil and protein powder (HempFlax, Netherlands) are extracted from natural fibre, e.g., hemp and flax.

Grass-based: Grass is a feedstock for producing organic fibres for biomaterials, fertilizer, biogas and CHP (Biowert GmbH, Germany), Organic fibres for biomaterials, fertilizer, biogas, lactic acid, amino acids and CHP (Green Biorefinery, Austria), and Organic fibres for animal feed, protein, minerals (fertilizer) (Grassa, Netherlands).

MSW and versatile waste-based: Bioethanol and chemical building blocks are produced by a variety of biochemical routes by LanzaTech from MSW, organic industrial waste and agricultural waste. Methanol and ethanol are produced by the gasification route (Figure 11) [70] from MSW by Enerkem. In addition, there is a range of waste biorefineries at the proof-of-concept stage [49]. Spinnova extracts cellulose microfibrils from a variety of resources, wood, leather, agricultural waste and textile waste by mechanical processes without using any chemicals as textile fibres.

Oily resource-based: Matrica Biorefinery, Italy (Novamont and Versalis) use thistle seeds grown on abandoned land in a range of chemical processes to produce plasticizers for polymers, additives for rubber, lubricants, glycerol, and cosmetic ingredients. Croda produces oleochemicals as polymers, lubricants, coatings, fragrances, and personal and home care products from oily crops and residues through chemical processes. Specialty polymers are targeted to improve the water resistance and durability of formulations, increasing effectiveness while reducing the frequency of applications, and saving the amount of product consumers need to use. The eco-range of surfactants is a 100% bio-based alternative to traditional ethoxylated products. 69% of raw materials come from natural renewable resources. KLK OLEO processes palm oil to produce oleochemicals for a range of applications, home, personal and health care, cosmetics & toiletries, food, flavors & fragrances, lubricants and industrial chemicals. Oleochemicals include fatty acids, fatty alcohols, glycerol, fatty esters, sulfonated methyl esters, surfactants and phytonutrients, etc.

Microalgae-based: Cosmeceuticals, nutraceuticals, proteins, oils, omega 3 and 6, carbohydrates and pigments are produced by Ecoduna, Austria, by extraction and isolation [29]. 100% Spirulina algae spray-dried for cell protection and energy. The blue-green microorganism contains high amounts of vitamin K and important antioxidants like vitamin A (ß-carotene) or phycocyanin. Spirulina is a source of iron and naturally contains vegan protein (up to 55%) as well as the trend ingredient spermidine. Spermidine is a biogenic, endogenous polyamine that is closely associated with cell growth and function. Phycocyanin gains more and more popularity through its antioxidant potential and its use as a coloring foodstuff. 100% Chlorella algae, carefully spray-dried, are for detox and energy. The green algae contain high amounts of the important antioxidant vitamin A (ß-carotene), as well as iron, folic acid and Vitamin B12. Chlorella is also a source of omega-3 fatty acids (alpha-linolenic acid) as well as the trend ingredient spermidine. Due to its high amount of chlorophyll, it is becoming more and more popular. It naturally contains vegan protein (up to 48%).

Coffee waste: International Coffee Organization (ICO) reported that about 170 million 60-kilogram bags (about 10 million tons) of coffee were produced worldwide in 2020/2021, which is equivalent to an average consumption of 1.25 kg per capita, with growing demand of more than 2% per year [79]. The largest producers are in Latin America, Asia, Africa, and Oceania [80,81], but most of the world’s production comes from five exporting countries, Brazil, Vietnam, Colombia, Indonesia, and Ethiopia. Mexico is the 11th largest producer in the world [79]. Among consumers, the European Union is the largest importer, with around 40% of all world trade, followed by the USA (24%) and Japan (6 %) [79,82].

In Mexico, this activity represents about 0.7% of the national agricultural and 1.34% of the production of agro-industrial goods, reaching an annual production next to 4.0 million of 60 kg/bags [80]. Projecting to reach 8.0 million bags of 60 kg by 2024, and 15 million bags by 2030. The main producers by state are Chiapas (41%), Veracruz (24%) Oaxaca (21%) y Puebla (15%), and the area devoted to coffee cultivation is just under 700,000 ha, according to the Secretaria of Agriculture and Rural Development (SADER). Yields are highly variable, depending on different factors ranging from management, climate, altitude, and variety, reaching general average yields of around 5.3 bags of 60 kg/bags/ha [83,84].

The negative aspect of coffee production is due to the extensive post-harvest processing, approximately 90% of the edible parts of the coffee cherry are discarded as agricultural waste or by-products, which generates a large amount of waste, both in producing and consuming areas. Thus, the harvest and production areas include various wastes or residues; leaves, flowers, husk, parchment, mucilage, and pulp obtained as solid residues [85]. While in the consumption areas, the main by-products are the silvers skin and spent coffee grounds (SCG), produced from coffee preparation in cafeterias or at home, as well as waste from the production of soluble coffee (instant coffee).

In quantitative and general terms, it is worth mentioning that for each ton of fresh coffee fruit, 180 kg of husks and around 150-200 kg of marketable green coffee are produced [85]. The coffee pulp and husk are the first by-products in the benefit areas (wet or semi-dry) and represent 30% and 18% of the total coffee cherry (dry weight), i.e., for each ton of commercial green coffee, 0.5 and 0.18 tons of pulp and husk are produced, respectively [86]. Both the husks and the pulp of the coffee are rich in carbohydrates, proteins, fats, and minerals, as well as a considerable content of bioactive compounds such as tannins, polyphenols, and caffeine [85,87].

On the other hand, the silver skin of coffee, which is the first by-product generated by the coffee industry, within consumption areas, is released during roasting. This residue has a low mass and comprises around 4% of the green coffee bean, which makes it difficult to recover and use it. However, it is rich in soluble dietary fibres and compounds with antioxidant capacity, especially due to the presence of phenolic compounds [85].

SCG are produced during the preparation of the beverage and includes waste from the soluble coffee industry. Keep in mind that for each 1 gram of ground coffee about 0.91 g of SCG is produced and for every kilogram of instant coffee about 2 kg of wet SCG is produced [85,86]. Its chemical composition depends on different factors, ranging from the variety of coffee, the extraction method, the degree of roasting, the degree of grinding, etc. As a result, around 6 million tons of SCG are generated each year worldwide from the production of instant coffee and brewed coffee, rich in hemicellulose, cellulose, lignin, fat, and protein [88]. Therefore, the management of SCG represents an environmental challenge and a great opportunity for its recovery and transformation into high-quality products. Among the options for their recovery and use, their use as a fertilizer stands out, due to its high N/C ratio, as raw material to produce ethanol with good yields, or the production of biogas by anaerobic digestion or co-digestion as an alternative to composting, and as fuel pellets [85,88]. SCG have also been found to have a high oil content, composed mainly of palmitic and arachidonic acids, which are saturated fatty acids, whose unsaturation provides good oxidation stability, as well as excellent cetane number and higher heating value [85]. Regarding its energy potential, the high H/C ratio, linked to high volatile carbon content, low content ashes, and heating values (LHV) close to 8.4 MJ kg^{-1}, for wet SCG and between 19–25 MJ kg^{-1} for dry SCG [86,87], making it an attractive raw material as a solid fuel. Considering the availability of this waste or by-product (~6 million tons) and considering its LHV as a reference, it is possible to estimate that their potential energy is around 50 TJ for wet SCG and between 114-150 TJ for dry SCG. Considering the availability of SCG or byproduct (~6 million tons) and its lower heating value (LHV) as a reference, it is estimated that its potential energy is around 50 TJ for a wet SCG (~50% moisture), and about 60 TJ, assuming a dry matter (<10% moisture) with the availability of SCG close to 3 million tons.

Within medical applications, the bioactive molecules, particularly the monoaromatic phenolic compounds, such as vanillic alcohol, eugenol, guaiacol, vanillin, vanillic acid, etc., present both in the coffee drink and in solid wastes, are an attractive option as free radicals' traps [91]. Oxidative or chemical stress is triggered by an excess of free radicals due to a wide variety of exogenous and endogenous processes [92]. In addition to oxidative stress, the benefits of caffeine for the treatment or control of type 2 diabetes [93] have been reported, without counting the potential of the oils or tars produced by pyrolysis from these residues or wastes in the treatment of psoriasis. Tars are one of the most effective, unknown, and oldest therapies for psoriasis. They include coal tar and biomass-derived products [94]. The above examples thus show the wide applicative scientific interest in the waste or by-products generated during the harvest, processing, and consumption of coffee.

Building on the evidence of sustainable biorefineries, the following recommendations are made for creating a sustainable circular bioeconomy.

1) Broaden the biomass choices: Mexico has a plethora of bio-based resources, following the EU definition, which can be sustainably developed and value-added in a synergistic and systemic manner. The implementation of a bioeconomy strategy can create new and unique opportunities for innovation, while simultaneously bolstering a country's overall innovative capacity and inclusive growth.

2) Sustainable biomass: The biomass of choice must be sustainable in terms of availability including seasonality, collection, storage and delivery to the site, and waste management. It is shown that large-scale multi-national biorefining companies have diversified their biomass portfolio and brought in farming communities or growers at the core of the developments through inclusive growth.

3) Product sustainability: Product selectivity, quality, consistency, stability of its production and scalability are important to evaluate and addressing these issues can introduce niche innovative high-value products to the market. Engineering biology is an important innovative field for integrated land management from biomass resourcing to product innovations.

4) Sustainable land management: Land is under competition for many bioeconomy-related reasons, nonetheless for food and feed production. Thus, land management, including soil quality, biodiversity and forestation, is fundamental to a sustainable circular bioeconomy.

5) Financing industrial biorefineries: A typical biorefinery with 220,000 tons per year production capacity requires an investment of ~750,000 USD. This is comparable to the petrochemical industry, thus, giving an opportunity to substitute petrochemicals with bio-derived chemicals.

Based on the sustainability analyses (Table 1) and the worldwide bioeconomy innovations, it is evident that there is potential for the development of a circular bioeconomy in Mexico. It is recommended that an integrated land management plan is evolved that promotes sustainable biorefineries in a whole integrated bioeconomy system across the country and its associated supply chains. The new bioeconomy policy could support diversity, inclusivity and global competitiveness for the country. As the bioeconomy by means of biorefining can keep a fine balance between the ecosystem and society, we see significant upliftment opportunities for poor marginal communities through equitable benefits. Bioeconomy inheriting circular economy at the core of the activities will underpin resource security and net zero for the country.

5. Conclusions

Here, we explored the status quo of Mexican policies relating to the B4 systems from the national policy literature. Like any other country, Mexico is undergoing an energy transition and therefore, it is time to develop a robust framework to support policies for developing the B4 systems in Mexico. The methodology consists of Mexico policy analyses, an approach to conducting a specialist workshop to validate our policy analyses on B4 systems and grey literature analyses to show how bioenergy can be cogenerated within biorefineries, a key ingredient to the circular bioeconomy. First, the related Mexico policies are analyzed to extract the essential points to discuss further at the workshop. Second, an expert workshop is held to gather evidence, which is further analyzed to synthesize the outputs. Third, grey literature is consulted to show biorefineries in Europe and other parts of the world. The Mexican policy analyses and workshop outcomes have both revealed a serious lack of biorefinery and bioeconomy systems thinking, deployment and regulatory frameworks to support B4 systems in an integrated manner. Despite some overlaps in the two policy landscapes between Europe and Mexico, the “interlinks: land and marine ecosystems and the services they provide; all primary production sectors that use and produce biological resources (agriculture, forestry, fisheries and aquaculture); and all economic and industrial sectors that use biological resources and processes to produce food, feed, bio-based products, energy and services (excluding medicines and health biotechnology)” are needed in Mexico’s policy landscape to direct their activities with the biological resources towards a sustainable circular bioeconomy. Moreover, biorefining is an important part of a circular bioeconomy. Biorefinery has been defined as “a facility with integrated, efficient and flexible conversion of biomass feedstocks, through a combination of physical, chemical, biochemical and thermochemical processes, into multiple products”. Biorefineries are sustainable when chemicals and materials are co-produced with bioenergy/fuel. Most industrial-scale biorefineries worldwide co-produce chemicals, materials and energy. The chemical and material yields are low in biorefineries, leaving most of the biomass for bioenergy generation. Their productions give significant global warming and fossil resource depletion potential savings. The majority of biorefineries worldwide produce Building blocks, Pharmaceuticals, Nutraceuticals, Cosmeceuticals, Paints & Coatings, Surfactants, Flavors & Fragrances, Lubricants, and Solvents, respectively, in the chronological order of their worldwide bio-based market share. After chemicals, material products dominate, with Polymers, Fibres, Composites, Resins, and Organic fertilizers, respectively, in the chronological order of their worldwide bio-based market share. In addition to product diversification, biomass diversification is recommended for resource security and sustainability. The biorefineries utilise sugar and starch-based crops, woody biomass, lignocellulose, grass, natural fibre, oily resources, etc. which are plenty in Mexico. Municipal solid waste, organic industrial waste, wastewater and micro and macro algae are also recognized as valuable resources for the ecosystem services and products. Our research indicates that prominent multi-national biorefining corporations have broadened their biomass range and integrated farming communities or growers into their advancements, emphasizing inclusive growth. Through the convergence of PND, LTE and the recommended bioeconomy policy, Mexico can attain sustainability and align with the UN SDGs. Our research provides compelling evidence in support of implementing a bioeconomy policy in Mexico.

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