

STANDARDS RESEARCH

Bioeconomy Landscape: Insights for Standardization

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Executive Summary

The bioeconomy has gained worldwide attention as a method to combat climate change and create employment opportunities. It is seen as an economical and environmentally sustainable way to limit greenhouse gas (GHG) emissions. An abundance of natural resources provides Canada with the unprecedented opportunity to produce biofuels and other bio-based products, positioning Canada as a global leader in the development of the bioeconomy.

This report presents an overview of bioeconomy processes and discusses the need to develop an integrated approach to bioeconomy advancements and regulatory and standardization activities that involves all stakeholders. It also identifies bioeconomy trends and recommends standardization areas that could enhance the bioeconomy in Canada. These trends and recommendations are based on a literature review and environmental scan of regulations and policies within the agriculture, forestry, and municipal sewage waste industries, as well as on surveys and interviews conducted with key bioeconomy stakeholders.

The bioeconomy is evolving rapidly and many innovative products have already been developed and are emerging in different sub-sectors. Given this accelerated growth, standards must be updated or developed to support the quality, safety, performance, and market competitiveness of bio-based products, as well as the profitability of bioindustries, while ensuring adequate feedstock supply. This report discusses the need for system level standardization, assessment of microplastics contamination of biosolids, combined heat and power systems (particularly in remote regions), and the need for bio-based content labelling and certification. It also presents potential pathways toward sustainable bioeconomy and sustainability criteria, along with driving forces and relationships within the bioeconomy.



"The bioeconomy was first proposed in the early 2000s, amid growing concerns about climate change and accelerating demand for materials, energy, and services, as a way to promote sustainable use of renewable resources in response to rising consumption."

1. Introduction

According to the European Commission, 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 biomedicines and health biotechnology [1, p. 4]. The terminology used to describe bioeconomy concepts is still developing, so a list of the terms used in this report and their definitions are provided in Appendix A1.

The bioeconomy was first proposed in the early 2000s, amid growing concerns about climate change and accelerating demand for materials, energy, and services [2], as a way to promote sustainable use of renewable resources in response to rising consumption. The bioeconomy is predicted to make significant contributions to limiting climate change [3]–[5] and mitigating greenhouse gas (GHG) emissions to restrict the global temperature increase to 1.5°C by 2050, as outlined in the Paris Agreement [6]. Hence, numerous efforts have been made to grow the bioeconomy around the world, and various regulations have been enacted in different jurisdictions, including Canada.

The bioeconomy's role in mitigating GHG emissions is conducted mainly through CO_2 sequestration and by offering alternatives to fossil-based fuels and materials. In 2018, the European Commission released its strategic long-term vision to achieve a carbon neutral economy (i.e., net-zero CO_2 emissions), which identified circularity of materials and sustainability of biomass as key elements to meet that goal [6], [7]. The circularity of materials is an essential component of the bioeconomy [8]. Specifically, circular bioeconomy refers to the management of bio-based renewable resources that integrates the principles of circular economy [9], initially known as the 3R (reuse, reduce, recycle) principles, with the goals of prolonging the value of materials, minimizing the use of resources, and reducing waste generation [10].

The circular bioeconomy is also an important part of any clean technology, which is "a means of providing a human benefit which, overall, uses less resources and causes less environmental damage than alternative means with which it is economically competitive" [11, p. 321]. Globally, clean technology initiatives were predicted to exceed $2.5 trillion by the end of 2022, and Canada plans for an annual clean technology export of $20 billion by 2025 [12]. To reach this target, faster deployment of clean technologies must be supported by increased testing and demonstration opportunities to meet quality, safety, and performance requirements. This will require the development of policies, regulations, and standards to help guide the bioeconomy. However, innovation, adoption, growth,

and commercialization of clean technologies are often impeded by existing regulations, which are built on old standards [12]. In cases where existing international standards are closely aligned with Canada's market opportunities, they should be adopted at the national level where possible to avoid any overlapping development of standards, while dated standards should be revised to facilitate innovation and the adoption of new clean technologies. Regulations will also need to be updated to reference new and current standards. Furthermore, to transform industries more quickly and to use the abundant natural resources in Canada, standardization must encompass products, processes, and practices that advance Canada's role as a world leader in the development of the bioeconomy.

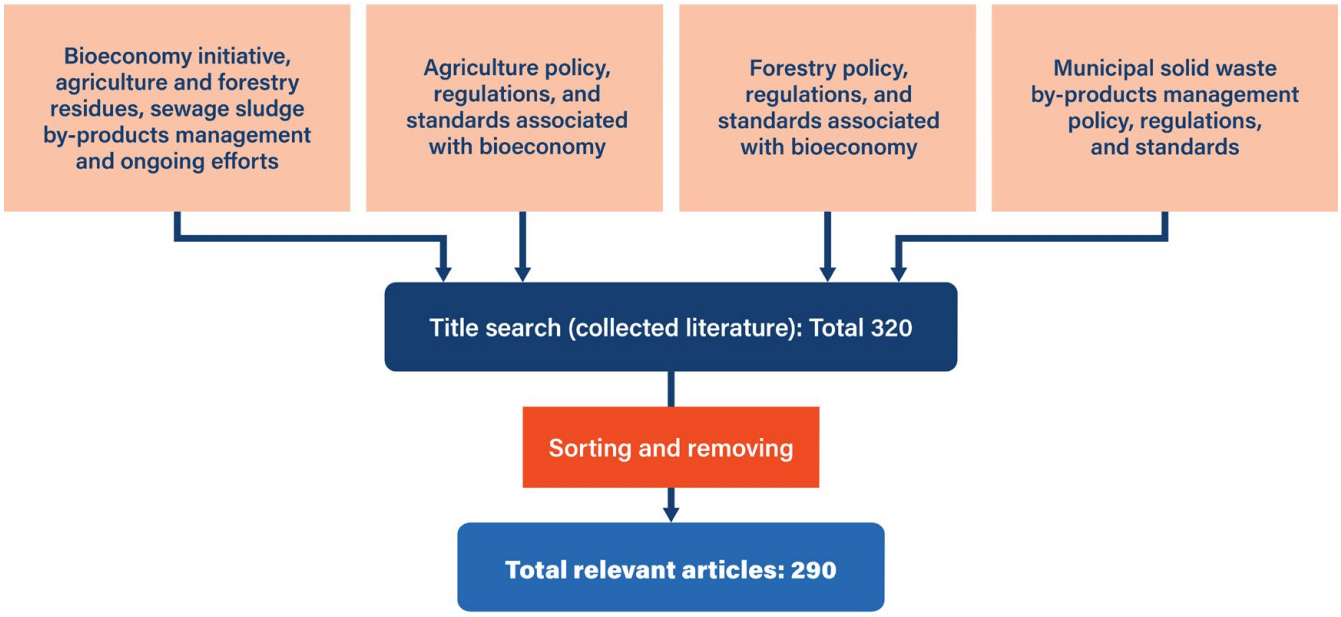
An abundance of forestry and agricultural resources provides Canada with the unprecedented opportunity to produce biofuels or bio-based materials for transition to bio-based solutions [13] and to contribute to the bioeconomy in general. For example, Canada has about 9 million hectares of marginal land that is not suitable for primary production [14], but can be used to grow biomass to produce biofuels and other bio-based materials and products. Annual biomass production estimates for agricultural residues, forest residues, and municipal solid waste (MSW) in Canada are reported to be about 120 million tonnes [15], [16]. In 2015, Canada generated approximately $4.3 billion in revenue ($2.9 billion of domestic sales and $1.4 billion in exports) from bio-based products derived from 21 million tonnes of biomass residues: 8.8 million tonnes of agricultural residues and 12.3 million tonnes of forest residues [17], [18]. This also created significant employment opportunities, engaging 5618 workers in 190 bio-based product industries [18]. Moreover, it is forecasted that the green economy, a low carbon, resource efficient, and socially inclusive economy [19] that includes the bioeconomy sector, will create 24 million jobs globally by 2030 [20], [21]. The annual growth of the Canadian bioeconomy is projected to be 1.5% and is expected to employ more than 223,000 workers by 2029 [22]. In Ontario, the forest industry alone generates $18 billion in annual revenue and is responsible for more than 148,000 direct and indirect jobs [23]. Annually, Canada invests approximately $31.6 billion in research and development in the forest sector [13].

The significance of the bioeconomy has been noted worldwide. In 2019, the European Union's bio-based chemical industry engaged 17.42 million workers and generated approximately €657 billion [24], accounting for about 3% of the domestic chemical market and contributing to Europe's 31% market share of global bio-based chemicals and materials. In 2017, the United States produced more than 65.4 billion litres of biofuels (cellulosic ethanol, renewable diesel, and other biofuels) and more than 2500 certified bio-based products (bio-based polymers, chemicals, pharmaceuticals, and adhesives), which created 4 million jobs and accounted for 2.5% of the United States economy [25].

Despite the benefits of the bioeconomy and emerging markets, there are growing concerns about the capacity for the arable land base to sustainably supply the demand for biomass [26]. Population growth combined with decreasing per capita land area and increasing needs for energy and food puts a lot of stress on arable land, water, and biological resources, which poses a critical challenge to the sustainability of many ecosystems. In certain use cases, food and energy production are associated with severe environmental and resource degradation that affects the ability of ecosystems to replenish themselves, thereby accelerating global warming and reducing biodiversity, and further increasing the threat to meet the rising demand for both food and biomass. The bioeconomy approach to increase dependency on biofuels to replace fossil fuels has the potential to increase pressures on natural resources while accelerating biodiversity loss and land degradation [27], [28]. This may create unequal distribution of the benefits from bioeconomy initiatives if appropriate policies are not put in place [29], [30].

Additionally, most of the innovations promoted under the bioeconomy label lack in-depth systematic evaluation of their potential sustainability and trade-offs [31]. For example, the application of biosolids as fertilizers could introduce or increase microplastics, which could contaminate the food system. Thus, crop production for biofuels and the application of biosolids must be regulated alongside the development of standards for biosolids that prescribe limits about the presence of microplastics.

Figure 1: Diagram of the literature collection methods used in this study.



Strategies for developing the bioeconomy must be carefully outlined, regulated, and standardized to avoid any unwanted rebound effects on the environment and society. To strengthen and achieve the desired goals of the bioeconomy in Canada, existing bioeconomy strategies must be reviewed and updated to meet the rising demand of biofuels and bio-based materials without compromising the needs of future generations.

This report identifies bioeconomy trends and opportunities for standardization related to the Canadian bioeconomy, with a focus on policies, regulations, and standards that apply to the agriculture, forestry, and municipal biowaste industries. This report also identifies barriers and potential pathways to improve standards for processing feedstocks and to improve the production of bio-based products within a sustainable bioeconomy.

2. Methodology

The research conducted for this report included a literature review and environmental scan of publications on bioeconomy policies, regulations, and standards, as well as bioeconomy trends. Google Scholar, Google Chrome, ScienceDirect, SpringerLink, and WorldWideScience were used to identify articles of interest using the following keywords: bioeconomy policy, bioeconomy regulation, bioeconomy standard, biomass production, agriculture, forestry, MSW, biomass producer, biomass distributor, and biomass exporter. In addition, the Standards Council of Canada, CSA Group, and International Organization for Standardization (ISO) websites were consulted for standards related to the bioeconomy that focus on biosolids, bio-based materials, solid and liquid biofuels, lignin, and nanomaterials (nano- and micro-cellulose). A total of **320** articles/reports/policy briefs were initially identified. After sorting, 290 articles were deemed relevant. Figure 1 shows the literature collection methods used for this research.

Each section shown in Figure 1 was reviewed by members of the research team, and insights on policies, regulations, and standards were summarized and further contextualized. Next, some of the constraints and challenges faced by each sub-sector were identified and discussed. Finally, potential policies, standards, and regulatory measures were assessed regarding their likelihood to strengthen the bioeconomy in Canada while mitigating risk to investment and protecting the environment.

The research also included surveys of relevant public and private sector stakeholders, including regulatory bodies, feedstock producers, and a range of for-profit and not-for-profit businesses associated with the bioeconomy. The surveys were used to gather stakeholders' opinions about gaps in standards related to the bioeconomy. Of the 116 stakeholders who were invited to complete the survey, 28 completed it (11 interviewees from public sector, 2 from academia, 3 from not-for-profit and 12 private sector). A subset of these respondents were also invited to participate in interviews to further discuss their perspectives on gaps in standards within the Canadian bioeconomy. Ten respondents agreed to participate in the interviews (the survey and interview questions are provided in Appendix: A2). Figure 2 provides a diagram of the stakeholders that were invited to contribute to this report.

3. Existing Policies, Regulations, and Standards

Technologies associated with the bioeconomy are often transdisciplinary, making it difficult for bio-based processes or products to comply with different sets of regulations. Moreover, the evolution of bio-based products is accelerating and some products may fall outside current regulatory structures. There is a need to improve regulatory frameworks in order to reduce investment uncertainty, high upfront costs for new businesses, cost and time of regulatory approvals, and feedstock cost, and to improve feedstock supply and financial assistance in the sector. A lack of adequate policies, regulations, and standards for evolving bio-based products can also affect the quality of products, potentially compromising their safety and hindering the development of a competitive market for innovation and for attracting investors [32]–[35]. Policies, regulations, and standards must be updated and developed for emerging bio-based products. A 2020 survey of 282 bioeconomy experts identified the need for greater intergovernmental cooperation and coordination at the international level as critical to achieving sustainable growth of the bioeconomy. The experts also advocated for stronger standards that incorporate sustainability criteria as well as support for innovation, incentives, and skilled workforce development [36].

3.1 Strategies and Policies

In 2012, the European Commission adopted a bioeconomy strategy to address challenges in food, energy, ecology, and the environment through innovative, efficient, and sustainable use of renewable resources without affecting food security [37]. They also called for joint public-private stakeholder efforts to develop competitive markets. The European Commission took a cross-sectoral approach to improve bioeconomy policy for environmental, economic, and social sustainability [24], [38]. The strategy is accompanied by a detailed action plan to (a) attract investment, create markets, and strengthen the bioindustry; (b) rapidly deploy local bioeconomies; and (c) improve knowledge of ecological boundaries of the bioeconomy. In 2020, the European Forest Institute released a 10-point action plan for a circular bioeconomy, which called for collective and integrated action of global leaders, investors, companies, scientists, governments, non-governmental and intergovernmental organizations, funding agencies, and society at large to put the world on a sustainable path [39]. In 2012, Germany outlined strategies for a bio-based economy that links technological, economic, and ecological issues by applying renewable materials in a more sustainable way to replace fossil-based resources while ensuring food supply and creating employment opportunities [40].

Canada published its national Bioeconomy Strategy in 2019 [41] and its Renewed Forest Bioeconomy Framework in 2022 [42], and is implementing several approaches to accelerate advancements and become a global leader in the bioeconomy using its abundant resources to produce bio-based fuels, bio-based materials, and bio-based chemicals for various industrial applications [41], [43], [44]. To support this transition to a sustainable bioeconomy, emphasis must be placed on biomass supply chain management, infrastructure development, value chains for bio-based products, and skilled workforce development while maintaining food security [41], [45]. Consultation with industry representatives also indicated that an advanced bioeconomy strategy must maintain an integrated approach to advance the sustainability of Canada's bioeconomy [41], [46], providing directions for future policy development.

Some provincial governments in Canada have also implemented strategies to help bioindustries thrive [45]. For example, Alberta has invested in its institutions to support the research and development of bio-based industries that use resources from the agriculture and forest sectors to enhance economic resilience, maintain growth, and provide employment opportunities [45]. In addition, Ontario is investing more than $14 billion a year in research and development efforts that include bio-based products [47]. Ontario has also collaborated with partners from the forest biomass supply chain to develop the Forest Biomass Action Plan, which presents the advantages of using Ontario's forest biomass, discusses challenges, and identifies ways to increase the use of forest biomass [23], [49]. In 2017, researchers suggested that Ontario's bioeconomy programs were fragmented and did not support all types of bio-based products or policy initiatives, and that a lack of a clear strategic direction had slowed Ontario's participation in the bioeconomy [48]. Therefore, coordinated actions of government, industry, and academia were necessary to align initiatives and foster an integrated approach in the bio-based products sector in Ontario. By 2022, the results of implementing such an integrated approach could be seen in Ontario's forest products' industry. For example, by-products from sawmills are supplied to bioenergy industries to reduce waste, promote circularity, and generate electricity for Ontario's electrical grid [49]. Furthermore, the Kenora Declaration on Forest Innovation, which emerged from the Canadian Council of Forest Ministers' National Forest Innovation Summit in 2015, exemplifies Canada's commitment to advancing innovation in the forestry sector through collaboration, engagement, and mobilization [13].

3.2 Regulations

Government and regulatory authorities play an important role in creating an environment for the transition to a more sustainable bioeconomy. For example, the United States Department of Agriculture (USDA) BioPreferred Program was established by the 2002 Farm Bill, which was expanded and re-authorized in 2018. The program was created to accelerate the development, purchase, and use of bio-based products by requiring government contractors and federal agencies to purchase bio-based products and by advocating for voluntary labelling and certification of bio-based products to make it easier for consumers to identify them [50]. Products carrying the USDA Certified Biobased Product label are certified for their bio-based content according to ASTM D6866 [51].

In Canada, bioeconomy strategies and regulations are tailored to various jurisdictions, so regulatory adjustments and streamlined policy strategies are required to create demand, competitiveness, and markets for bio-based products in order to elevate this growing sector.

The House of Commons Standing Committee on Natural Resources identified four areas of priority for Canada to achieve the full potential of the forest-based bioeconomy [52]. One of the priorities, to maximize forest-based products market opportunities, was exemplified by the following opportunities:

- Use of bio-based fuel, such as wood pellets, to replace coal for power and heat generation;
- Blending biodiesel for higher-grade blended fuels to support Canada's proposed clean fuel standard, which aims to increase the use of lower-carbon fuels and alternative technologies, including renewable fuels, with the objective of reducing annual GHG emissions by 30 million tonnes by 2030 [53];
- Establishing value-added products from existing forest-based industries, such as integration of pulp and paper mills with municipal district heating systems, biorefineries, or carbon capture and storage technologies; and
- Use of forest bio-based products (lignin, cellulose, bark) as alternatives to petrochemicals in various industrial applications (aerospace, polymers, adhesives).

Canada also enacted the Greenhouse Gas Pollution Pricing Act 2018, which puts a price on all GHG emissions and promotes the use of renewable energy to grow the Canadian economy while reducing GHG emissions in alignment with the Paris Agreement [54]. In addition, the Canadian Fertilizer Regulations were amended to include municipal biosolids in the list of



"There are additional opportunities that could facilitate the Canadian bioeconomy, such as restructuring pulp and paper industries to produce more value-added products from forest by-products."

primary fertilizer materials [55], and Ontario amended its General Regulation under the Nutrient Management Act to reduce the regulatory burden on businesses by allowing farmers to produce biogas from food and organic waste in anaerobic digesters while using digestate as fertilizers [56], [57]. Furthermore, Canada amended the Reduction of Carbon Dioxide Emissions from Coal-fired Generation of Electricity Regulations (SOR/2018-263) to phase out coal by 2030 [58], which has paved the way for the development of biochar.

Ontario has also streamlined some procedures in other sub-sectors of the bioeconomy. For example, Guidelines A-13 and A-14 deal with the control of air emissions from large and small wood-fired combustors, respectively, and promote the use of wood fuel as a renewable energy source. They establish minimum expectations for air quality and make the permitting process for EN 303-5 Class 5 wood-fired combustors cheaper and quicker [59], [60]. In addition, amendments to regulations under Ontario's Environmental Protection Act and Environmental Assessment Act included exemptions for combined heat and power (CHP) systems and wood-fired combustors between 50 kW and 150 kW under Section 9 of the Environmental Protection Act [61]. This exemption removes requirements for Environmental Compliance Approvals and Renewable Energy Approvals, ensuring that CHP systems that use biofuel are subject to the same regulatory requirements as other systems with equivalent environmental and human health impacts.

There are additional opportunities that could facilitate the Canadian bioeconomy, such as restructuring pulp and paper industries to produce more value-added products from forest by-products, which would create new markets for bio-based products as well as new jobs [62]. In addition, there is no coordinated and integrated policy framework for the Canadian biofuel industry [63]. The only regulations that address biofuels are the Clean Fuel Regulations, which address the mixing of ethanol with petroleum-based fuel, so the requirements are only relevant for gasoline and diesel that need to meet annual emission reduction targets; no other bio-based fuels such as bio-oil are included [64]. Consequently, other liquid biofuels and emerging bio-based products need to be regulated for a smooth transition to the bioeconomy.

3.3 Standards

There are numerous national standards and industry standards in the bioeconomy field, and they cover a wide range of topics, from analytical procedures of biomass to the quality requirements of bio-based products, including biofuels and bio-based chemicals and materials. A list of certain agricultural and forest-based products standards is provided in Appendix A3, and a more comprehensive list for bioenergy, bio-based materials, bio-based chemicals, and biofuels is available through the Biomass Quality Network Canada database [65].

In addition to standards produced by standards development organizations through the collaboration of all relevant stakeholders, some standards are developed by industry associations to fulfill quality requirements of the producers. For example, the International Biochar Initiative's IBI-STD-2.1 serves as the basis of their Biochar Certification Program, which certifies biochar manufacturers in Canada and the United States whose products meet specifications for biochar that is used in soil [66]. However, they do not certify products that are mixed with biochar, nor do they consider issues of sustainability, such as climate change mitigation.

There are several standards that address management and future use of forest and land resources. In North America, the Sustainable Forestry Initiative has developed a number of standards on that topic, including Fiber Sourcing and Forest Management [67], which includes a fire resilience and awareness objective that requires certified organizations to reduce the susceptibility of forests they own or manage to wildfires and to inform communities about the impact and minimization measures of forest fires, while reinforcing the importance of protecting Indigenous people's rights by ensuring forests are appropriately cared for. The Forest Stewardship Council (FSC), an international organization with a Canadian chapter, also has a forest management certification program [68]. FSC has revised several policies and standards to address loopholes regarding ownership, particularly the conversion of natural forest-related ecosystems into plantations and its processes, which (a) help reduce forest fires and risks to ecosystems through management practices; and (b) enhance forest biomass yield by stimulating the forest sector to supply more feedstock for bio-based products and contribute to the bioeconomy [68]. Relevant FSC standards are listed in Appendix A3.

The Roundtable on Sustainable Biomaterials (RSB), a global organization, has developed a standard that focuses on sustainability of the bioeconomy by mitigating key environmental and social issues around the use of bio-based fuels and products, such as deforestation, water pollution, and global hunger. Though compliance with the RSB Standard, and through RSB certification, producers and processors of feedstock, bio-based fuel, and bio-based products ensure they are achieving and exceeding the minimum levels of environmental stewardship compliance established in the 2009 European Union Directive [69].

To facilitate investments in the bioeconomy, Ecostrat, a global consultancy firm, has developed the Biomass Supply Chain Risk (BSCR) Standards to assess and mitigate the risks for capital investment in bio-based products and to promote faster and more affordable biomass delivery in North America [70]. This, in turn, will help to alleviate concerns about securing a steady supply of quality feedstock [71]. The BSCR Standards, which served as the basis for CSA W209, *Biomass supply chain risk,* a National Standard of Canada, address investment risks in six categories:

1. Suppliers
2. Competitors
3. Supply chain
4. Feedstock quality
5. Feedstock scale-up
6. Organizational internal risks (feedstock cost, inventory, management, and personnel) [70]
7. Estimates and Limitations of Biomass Residue Extraction in Canada

4. Estimates and Limitations of Biomass Residue Extraction in Canada

The cost of feedstock logistics (harvesting, collection, and supply/transportation) and feedstock quality, as well as the lack of matured biorefinery technologies and cost-competitive bio-based products, are significant barriers to achieving a sustainable bioeconomy.

Agricultural and forest residues, purpose-grown energy crops, and MSW are the main sources of bioeconomy feedstock [72]–[75]. Canada has abundant biomass resources [76], [77]. With nearly 400 million hectares of forest land [77], Canada produces approximately 21 million dry tonnes of logging residues per year [78], which are usually piled on the roadsides or left in windrows to decay [79], [80], posing a risk of fire [79]. Sawmill residues are typically processed by

pulp and paper industries (15.8 million tonnes), so unused sawmill residues are limited [81]. For example, to balance the feedstock demand for bioenergy in 2013, an estimated 1.3 million dry tonnes of sawmill residues were required in addition to the approximately 8.5 million wet tonnes that were used [81]. However, in Newfoundland, thousands of tonnes of wood products waste is being stockpiled at municipal waste management dump sites and approximately 4000 tonnes of waste is added every year [82].

Some of the interviewed stakeholders suggested that accessibility and extraction of forest logging residues is hindered because of inadequate road systems and their maintenance in remote areas, complexities of navigating the land or resource ownership, and lack of suitable equipment for collection and pre-processing, as well as costs associated with collection and transportation and market price [79]. Furthermore, the extraction of forest residues is subject to numerous policies, standards, and guidelines [83], which preserve nutrient balance in forest soil [84] and protect forest ecosystems [85]. To secure the availability of forest residues along with a stable market price, strategic partnerships with forest logging companies and woodlot owners must be established to better assess the forest residues inventory and supply of forest fibre to emerging bioindustries [13]. Analysis of forest biomass supply chains confirmed that transportation of untreated and bulky residues for distances longer than 50 km to 150 km would not be energy efficient or economical [86], [87], and transportation distances over 60 km and 100 km would not be economically recoverable at a "bioenergy facility gate" price of $50 and $60 per dry tonne, respectively [88].

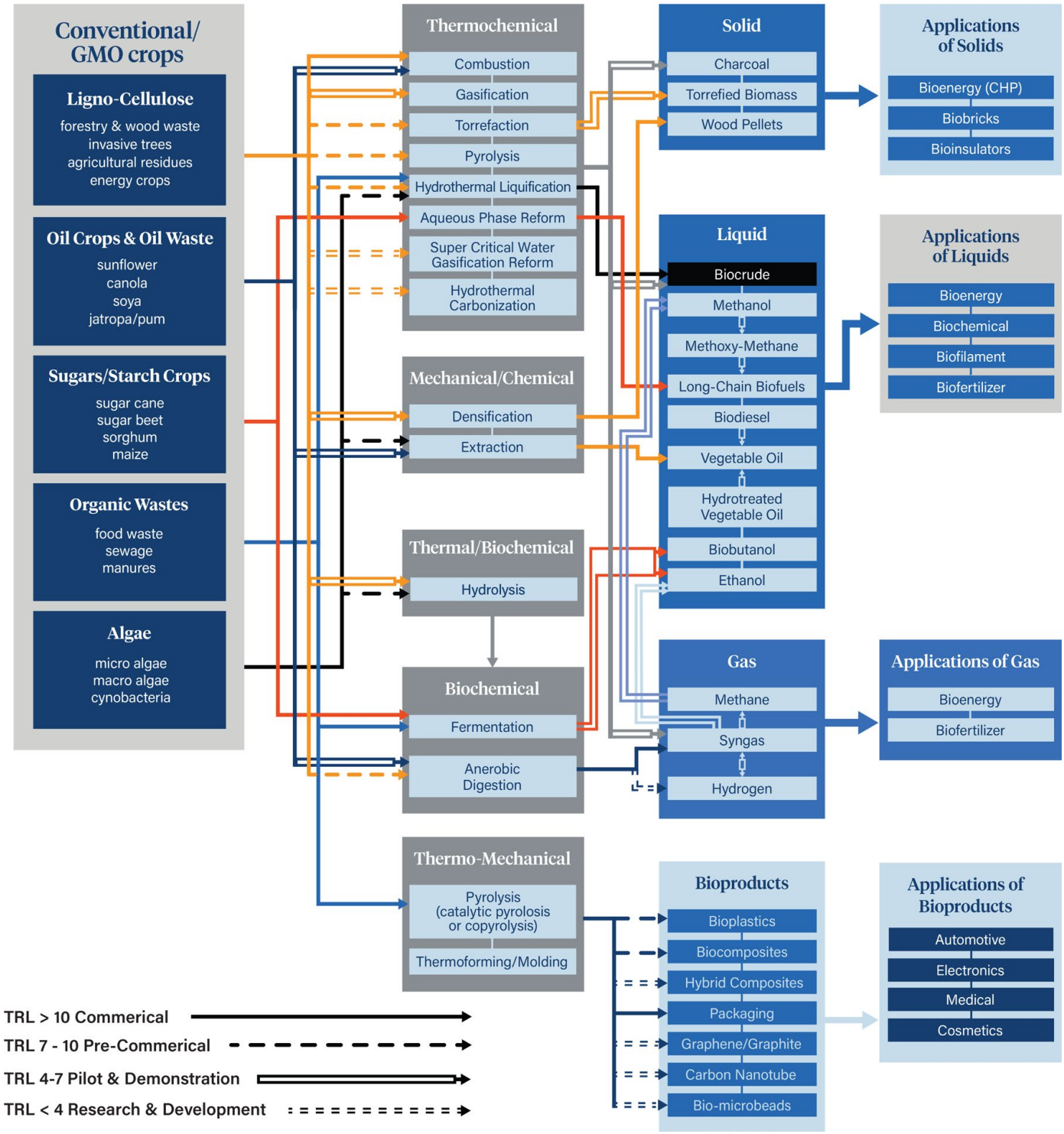
The annual production of agricultural residues in Canada is estimated to be about 48 million dry tonnes [14]. These biomass residues could provide 20% of Canada's yearly energy supply [89], but in 2020, bioenergy only accounted for about 6% of Canada's total energy supply [90]. The collection and use of agricultural residues for bioindustries is limited by farmers' concerns about soil quality and their reluctance to harvest crop residues. Soil degradation has been reported to cost Canadian farmers about $1 billion a year [91]. It has been proposed that the collection of corn residues without soil degradation must be restricted to between 30% and 50% [92], [93], or to 40% and 70% from continuous corn production and no till production, respectively [94]. An additional restriction for agricultural residue collection is a usual transportation distance of more than 50 km for processing of bio-based products [95]. Consequently, to implement large-scale applications of crop residues, these barriers (concerns over soil quality, markets for residues, biomass logistics, and farm income) must be overcome.

MSW production in Canada was estimated at about 34 million tonnes in 2016 [96] and 35.5 million tonnes in 2018 [97]. Of that, about 25 million tonnes of MSW was sent to landfills and about 9 million tonnes was used for material recovery [96]. Moreover, about 3% of MSW requiring final disposal in Canada is incinerated [98]. Every year, wastewater treatment plants process sewage sludges to produce about 666,000 dry tonnes of biosolids, which are typically used in agriculture to replace inorganic fertilizers [99], [100]. Compost from organic waste and digestate from anaerobic digestion processes have also been applied in agricultural fields. MSW that is currently being sent to landfills could be diverted to relevant bioindustries under a contractual agreement. The use of such an industrial symbiosis approach would ensure a steady and smooth feedstock supply, reduce transportation distances, and create partnerships among bioeconomy stakeholders.

5. Current and Emerging Technologies and Bio-Based Products

Biomass is used in a variety of value-added products processes. Figure 2 presents a high-level overview of the commonly applied steps for feedstock conversion technologies that are currently in use or in the development stage. It shows prospective end uses of bioenergy and bio-based products and the technology readiness levels (TRL) adopted from [101], [102], [103]. It should be noted that while many conversion technologies are being integrated, such as integrated biorefinery and biotechnology advances [25], [104], [105], for simplification purposes, they are not all listed in Figure 2.

Figure 2: Feedstock conversion technologies and their products.





"Bioenergy with carbon capture and storage (BECCS) is also gaining attention, both as means to achieve net-zero emissions and as a way to enhance the bioeconomy."

Bio-based products that are currently being developed (TRL < 4) include ultralight composites for electric vehicles and the electronics industry, emerging food packaging, and biodegradable plastic mulch, which is commonly made of bio-based polymers such as polylactic acid (PLA), starch, cellulose, and polyhydroxyalkanoates (PHA) [106]. PLA and PHA are widely used in many commercial products, including drug capsules [107], disposable tableware and cutlery [108]–[110], plastic films, adhesives and coatings, and 3D printing filaments [111]. PLA production has yet to be commercialized in Canada. In Europe, the major PLA producers include NatureWorks and TotalEnergies Corbion [112], while BASF produces a polymer of PLA and polybutylene adipate terephthalate [113]. Specialty PHA is being produced in Canada by TerraVerdae Bioworks [111], and the Korean company, CJ Bio, is a leading global producer of PHAs [114]. The co-processing of multiple feedstocks is also gaining attention due to improved product yield, quality, and conversion efficiency [115], [116].

For bio-based chemicals, several important developments are underway, including bio-naphtha, which is being commercially produced by UPM, Preem, Neste, and others [117]. In addition, although not commercially available yet, UPM is developing bio-based ethylene glycol and propylene glycol [118] to replace fossil fuel-based glycols in a variety of applications, and both Stora Enso and Avantium will produce furan dicarboxylic acid [119], [120] to replace terephthalate in polyethylene terephthalate (PET) to create polyethylene furanoate (PEF) [121]. According to some of the stakeholders consulted for this report, the quality of these bio-based polymers are expected to follow the criteria for non-bio-sourced materials, and adaptation of European standards should be considered.

Pyrolysis is another rapidly evolving technology in the bioeconomy. Although various types of reactors are used in pyrolysis, when establishing a new facility, it is important to select a reactor that meets the needs of specific bioeconomy jurisdictions. For example, fluidized beds and rotating cone configurations are easier to scale-up and are more cost effective [122].

Bio-based carbon materials, such as graphite, graphene, and carbon nanotubes, have the potential to produce the next generation of advanced composite materials for many industrial applications. For example, graphitic bio-sourced carbon was developed as an alternative carbonaceous functional filler for polymer and bio-based composites [123].

Bio-based composites are gaining attention for use in the production of lightweight electric vehicles. In Canada, a hemp bio-based composite was used in electric car manufacturing processes to reduce tooling costs [124]. In addition, a bio-based resin (polybutylene succinate) was developed as porous foam, and its flame retardant and heat barrier properties were improved by integrating functionalized graphene oxide [125]. In Canada, West Fraser Mills is exploring potential markets for their pulp-based composite, Propel [126], and in Europe, Stora Enso and UPM have already commercialized some wood-based composites [118], [119].

Bioenergy with carbon capture and storage (BECCS) is also gaining attention, both as means to achieve net-zero emissions and as a way to enhance the bioeconomy. It involves capturing CO_2 produced during the conversion of biomass to energy and then permanently storing it in a suitable geological formation [127]. Canada is a leader in carbon capture and storage (CCS) technology, and CSA Group manages the activities of the ISO technical committee on Carbon dioxide capture, transportation, and geological storage (ISO/TC 265). Canadian CCS projects include Boundary Dam, Quest, and Weyburn-Midale [128]–[130]. The United States established a Regional Carbon Sequestration Partnership with more than 400 organizations in 43 states, as well as four Canadian provinces, to support research for storing CO_2 through CCS field projects. The partnership conducted 19 small-scale field research initiatives and developed the required framework to validate that geological carbon storage is underway [131]. As of 2019, there were 23 large-scale CCS projects globally, either in operation or under construction, with the capacity to capture 40 million tonnes of CO_2 a year, predominantly from natural gas processing and chemical manufacturing [3]. Investment in BECCS projects is growing in different jurisdictions, including in the United Kingdom and North America, where Drax has invested in BECCS projects [132]. Deployment of large-scale BECCS has been shown as key for limiting the average temperature increase to 1.5°C or 2°C, as outlined in the Paris Agreement, and while BECCS can substantially change land use if driven by economics alone, research has projected that global food prices would increase by an average of less than 5% [133]. Nonetheless, the large-scale application of afforestation and BECCS have the potential cause geopolitical conflicts about (a) determining who should provide the territory and set up the facilities, and (b) the use of land resources [134]. Deployment of large-scale BECCS projects also raised concerns about socioeconomic impacts [135], environmental impacts, and impacts on freshwater systems [136], [137], as well as on food prices and food security [138]. Technological advances and policy initiatives may dictate the viability of CCS and BECCS [3].

Finally, the nature-based solutions of afforestation and reforestation have demonstrated potential to reduce emissions and remove atmospheric CO_2 while safeguarding food security and biodiversity [139]. However, until 2011, Alberta had the only regulatory strategy incorporating bio-carbon offsets that allowed soil carbon offsets [140]. Another nature-based solution, microalgae that use CO_2 to produce biofuels, bio-based materials, and extracellular polymeric substances, as well as carbohydrates and lipids, also have potential to contribute to climate change mitigation [141] and the bioeconomy.

6. Critical Needs and Potential Gaps in Codes and Standards

6.1 System Level Standardization

Stakeholders who responded to the survey advocated that standards should focus on system level transitions to a net-zero emissions economy. For example, standards on the collection of agricultural and forest residues should specify the amount of residue that must be left uncollected to support soil health. Moreover, energy crops cultivated for feedstock should not affect the food supply or compete for land with food production.

Similarly, industry's capture, storage, and use of carbon could be mandated by regulations, and societal acceptance of the technologies could be heightened through advocacy efforts. Many of the respondents also argued for a broad life cycle assessment of bio-based products to determine their potential in the bioeconomy as well as their sustainability. Although the ISO Life cycle assessment technical committee (ISO/TC 207/SC 5) has developed general guidance for life cycle assessment, standards specific to logistics, properties, and bio-based products should be developed, and their socioeconomic and environmental prospects defined. Table 1 lists issues associated with bioeconomy trends and gaps, and standardization, policy, and regulatory opportunities that may help expedite the bioeconomy in Canada.

Table 1: Bioeconomy Trends and Gaps and Standardization Opportunities

Bio-based material or product	Trends and gaps	Standardization, policy, and regulation opportunities
Bio-based products§	Lack of consumer awareness about the beneficial environmental impacts of bio-based products.	Develop standards for consumer-facing labelling that identify bio-based products' environmental impact and describe methods for calculation and CO_2 emission-based rating using life cycle assessment and labelling criteria. CSN EN 16760 [142] provides guidance and requirements to measure environmental impact of bio-based products.
	Number of emerging bio-based products are increasing due to initiatives to combat rising GHG emissions by reducing dependency on fossil fuel-based products.	Develop standards for emerging bio-based products prior to their commercialization, or update relevant standards with appropriate requirements.
Feedstocks	Costs of harvesting, collecting, and maintaining a consistent supply of feedstocks can be higher than for petroleum-based products or other carbon-intensive alternatives.	Develop policies that encourage consumers to purchase bio-based products in order to support bio-based products that have overall lower carbon footprints.
Soil amendment products*	Biosolids, bio-based carbon, and compost containing microplastic contaminants (originating from either biodegradable or synthetic plastic) can be detrimental if introduced into cultivatable land.Data on contamination of these products by microplastics originating either from biodegradable plastics or conventional plastics is scarce.Reviewed standards or regulations for the application of biosolids or bio-based carbon for soil amendment do not to address microplastics. ISO 19698 refers to jurisdiction limits on foreign matter content (including plastics) in land applied biosolids, and does not specifically address microplastics [143].	For jurisdictions without microplastics restrictions, standardization could help establish acceptable levels of microplastics in bio-based soil amendment products. Similarly, standards and regulations for recycling of MSW could prescribe requirements for the level and type (biodegradable or synthetic) of microplastic that can be introduced into bio-based products or soil amendment bio-based products. ISO/TC 61/SC 14 is currently developing ISO/FDIS 24187, Principles for the analysis of microplastics present in the environment [144], and ASTM D8332 details sample collection methods for identification of microplastics in water [145].
Biofuels and feedstock†,‡	Increasing biofuel production and its uses may change current land use patterns, which could adversely affect the food supply.	Develop standards or guidelines to ensure biofuel production does not adversely compete with food production in Canada. Adoption and modification of CEN EN 16214-3 should be considered [146].
	Lack of evaluation to determine environmental impacts of marginal land use scenarios, such as carbon sinks vs. biofuel crop production.	Develop standards to uniformly quantify the relative carbon storage potential of marginal land across the borders, whether land is used for biofuel crops or left protected.
	Rising demand for liquid biofuels means ethanol is being produced both from food crops and from lignocellulosics, so the quality of ethanol co-products/by-products varies.	Standards are needed to determine quality criteria of ethanol production by-products used in various applications, such as distillers' dried grains with solubles.

Bio-based material or product	Trends and gaps	Standardization, policy, and regulation opportunities
Bio-based carbon[†, ‡, §]	Bio-based residues high in inorganic elements reduce thermal efficiency of biochar processing equipment. However, biochar rich in nitrogen is preferred for soil applications.	Because some biochar can be high in nitrogen content, standards for biochar used for heating should limit nitrogen content, while standards for biochar used for soil amendment should specify minimum nitrogen content.
	Various applications of bio-based carbon, such as soil amendment, heat and power generation, carbon sequestration, bio-based composites, or secondary bio-based materials, require products with different properties.	Develop standards for bio-based carbon for each specific application.
Bio-coal[†, ‡]	Application of bioenergy in rural communities is gaining attention in off-grid and remote regions, especially in northern Canada.	Develop policies and guidelines for resource extraction to make more economical feedstock available for CHP. Rural communities require a range of feedstock to be processed and made available for CHP projects.
Lignin[§]	Value-added bio-based products, such as asphalt mixes and carbon fibres as fillers, are being tested for use in Canada. FPInnovations is conducting a feasibility study on use of lignin-modified asphalt pavement in Canadian conditions [147].	Should these new technologies prove to be applicable, standardization of practices and product quality should be undertaken. Develop standards for various grades of lignin based on their end uses, which will facilitate a competitive market for lignin.

Notes. GHG: greenhouse gas; CHP: combined heat and power; MSW: municipal solid waste. Critical needs and potential gaps described in Sections 6.1 and 6.6 apply to all products listed in the Table. Other applicable sections descried as: [*]Section 6.2, [†]Section 6.3, [‡]Section 6.4, [§]Section 6.5

6.2 Microplastics

Biodegradable plastics, commonly produced from renewable raw materials, are gaining popularity in efforts to replace conventional plastics and mitigate waste problems [148]. Although biodegradable plastics degrade faster than synthetic plastics and completely degrade in industrial composting facilities [148], they also generate microplastics that can leak into the environment [149]–[151]. For example, microplastics from starch-based plastics were shown to have a greater negative impact on wheat growth compared to microplastics from polyethylene plastics [152]. Consequently, policies, regulations, and standards need to be developed to address these known problems and to help prevent negative impacts on the bio-based plastic market, which had an estimated global worth of USD 10.2 billion in 2021, and is projected to be worth about USD 12 billion in 2030 [153], while the total market for bio-based polymer and plastic is predicted to be about USD 30.0 billion by 2039 [154].

The presence of microplastics is also an issue in sewage waste, sludge, and composted sewage sludge from wastewater treatment plants that are typically applied to agricultural land for soil amendment. The concentration of microplastics in biosolids was measured to be between 8678 and 64,986 particles per kg of dry sewage sludge [155]–[157]. In Canada, the concentration of microplastics in biosolids was estimated to be between 4400 and 14,900 particles per kg of biosolid, while biosolids used to treat farmland are estimated to add 1518 tonnes of microplastics per year [157]. The concentration of microplastics in farmland soil increases with successive application

of biosolids [158], and microplastics have been shown to be entering the food systems [159]–[161]. Plant-root systems, particularly those of vegetables, absorb plastic particles (~0.2 µm), which then migrate to shoots, making it more likely the particles will enter our food systems [162], [163]. Although the Canadian Fertilizer Regulations include biosolids in the list of primary fertilizer and supplement materials [164], microplastic content in biofertilizers is not specifically addressed in the definition of biosolids.

Furthermore, two Canadian standards that specify content and characterization methods of biosolids as soil amendment (CAN/BNQ 0413-400) and composts as soil conditioners (CAN/BNQ 0413-200 [165], [166]) also do not specifically address microplastics. It appears that only CAN/CGSB-32.310 [167], the Canadian standard for organic food production systems, indirectly addresses the issue of microplastics by prohibiting the use of sewer sludge as a soil amendment. Hence, standards and regulations are required that address soil amended for non-organic food in order to prevent exposure to microplastics and ensure food safety. This also applies to biochar that is used as soil amendment and is produced via co-pyrolysis.

6.3 Mobile Equipment

A successful bioeconomy industry relies on the balanced development of biomass supply chains [102], which means that any high logistics costs must be addressed. One solution that has been developed for the issue of transportation costs in remote regions that are significantly distant from plants is mobile equipment to produce biochar and bio-based products from forest or agricultural residues. For example, mobile pyrolyzers provide a potential pathway for converting feedstock into multiple products, such as biochar, bio-oil and syngas, so potential standardization in this area could focus on implementation of mobile pyrolyzers.

6.4 Bioenergy in Remote Regions

The use of bioenergy in rural communities is gaining attention in off-grid and remote regions, especially in northern Canada, because it offers energy self-sufficiency, reduced energy costs, and employment opportunities. In Canada, 250 remote communities that rely on fossil fuels for their heat and power would benefit from alternative energy generation, such as from CHP using biofuels [168]. To meet this level of demand, a variety of feedstock needs to be processed and made available for CHP projects. Standardization of the resource extraction phase could help make biofuel more economically feasible.

6.5 Novel Applications of Bio-Based Products

To support new and emerging bio-based products in Canada, it is essential to build and strengthen consumers' trust and acceptance of the bioeconomy, as well as their preference for these products. Standards that ensure safety, quality, performance, and sustainability are required to achieve these goals, and their adoption in regulations is equally important. The stakeholders surveyed for this report confirmed that bioeconomy standards for emerging products are needed to enhance competitiveness and to control the quality of products on the market in order to improve safety. They also indicated that standards should address feedstocks, processes, and products, and should consider the specificities of feedstock originating from the same source but being used for different products, as well as the use of products in specific applications.

Agricultural residues are usually high in inorganic elements, which reduces their calorific value when used as an energy source [169]. Therefore, agricultural feedstock should have limits on the amount of inorganics allowed for further processing into fuels. Similarly, feedstock of smaller particulates should be processed in pyrolyzers to avoid agglomeration and related issues of clogging or blocking reactors, as reduced agglomeration has been reported when using smaller feedstock particle sizes [170], [171]. Agglomeration issues can also be reduced through alternate bed materials, duel-fuel biomass blends, and processing parameters [169], and one study used an ablative reactor to convert whole wood chips and wood rods into bio-oil, thereby avoiding the grinding energy requirement [172]. Consequently, requirements for feedstock size must also consider processing equipment and feedstock conversion technologies.

The chemical and physical characteristics of bio-based products are equally important and should be included in standardization efforts. For example, bio-based carbon is used as a filler material for lightweight automotive components [173]–[175], building materials [176], wastewater treatment [177], [178], and as soil amendment [179], [180], and has received significant attention for its use in CCS [181]–[183]. However, bio-based carbon's properties depend on the feedstock used to make it, which also determine its application. For example, biochar derived from agricultural residues contains a higher concentration of nitrogen than biochar derived from energy crops or woody biomass [184], [185]. Biochar with high nitrogen content is preferable for use in soil amendment, while low nitrogen biochar is more suitable for fuel as it will emit less nitrous oxide compared to biochar with high amounts of nitrogen. However, the low density and relatively weak mechanical properties of biochar, as well as the high CO2 reactivity, make it undesirable for ferroalloy production [186]. Standards for bio-based carbons used for specific applications must be further explored and developed.

With the development of nanocellulose technology, standards need to address the novel applications of nanocellulose, including its uses in biomedical, 3D printing, electronics, and textiles applications, such as the use of cellulose filament as a reinforcing agent in the paper-making process. In 3D printing, the printability or extrudability of cellulose-based materials are vital properties for quality printed constructs [187]. Furthermore, the hydrophilicity and lower thermal stability of cellulose nanomaterials used in composites restricts the choice of polymers [188], [189] and the processing methods [189].

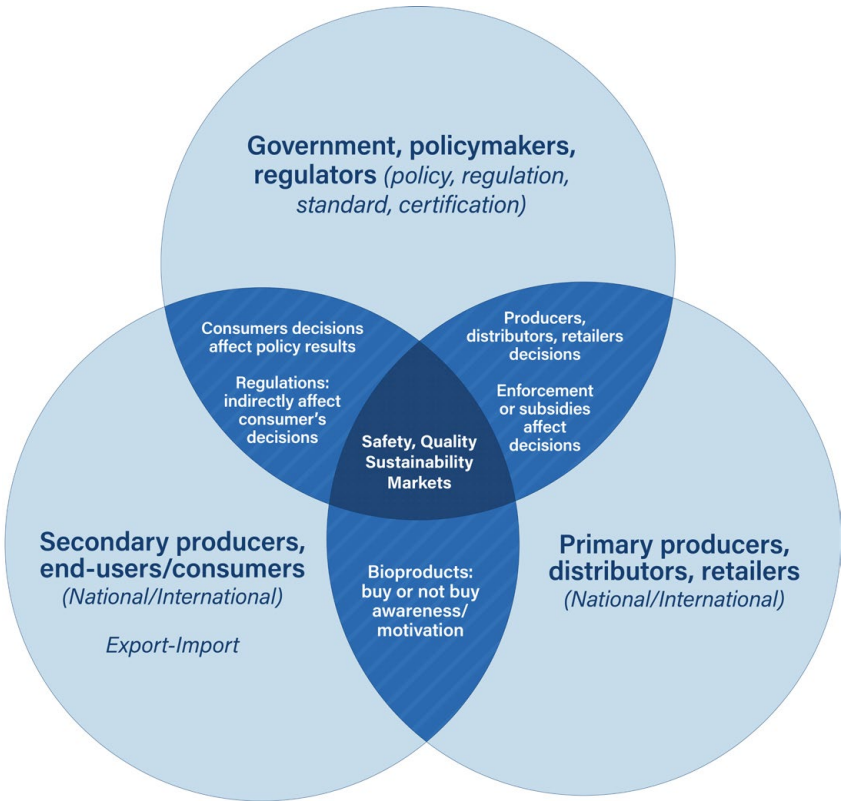
Similarly, lignin has a wide range of applications that require different grades. Although there are standards for the quantification of lignin composition, such as CSA W213 [190], standards that address the quality of lignin products based on their end-use applications also need to be developed. Lignin can be used as value-added bio-based products (resins, additives, acids), as filler (plywood boards), or to replace bitumen in asphalt mixes [147]. West Fraser commercially produces lignin for use as an adhesive for engineered wood products in its Hinton mill in Alberta [191]. In Europe, UPM has referred to lignin as the "new normal" for the phenolic resin industry [192]. Lignin has also been used to replace styrene in acrylonitrile-butadiene-styrene to produce acrylonitrile butadiene lignin, which is commercially produced by Prisma Renewable Composites and its industrial partner Yanfeng Global Automotive Interiors [193]. The use of lignin for road pavement has been tested in Europe, but the feasibility of using lignin and the quality requirements in asphalt mixes needs to be tested in the Canadian climate [147]. Canada's annual bitumen market is approximately 4 million tonnes. The adoption of lignin in asphalt applications within the Canadian context might require a new standard. Lignin is also widely used to produce carbon fibres, whose quality is governed by both manufacturing processes and lignin properties [194]. It should also be noted that lignin can be extracted from various sources [195] and its applications depend on the residual sodium content [196].

In addition to these new and emerging bio-based products, there is a need to consider standardization of the emerging by-products of the bio-based industry. For example, with the rising demand for liquid biofuels, the ethanol industry is expanding and producing ethanol from both food crops and from lignocellulosic feedstock, so the quality of co-products or by-products of the ethanol industry varies. Distillers' dried grains (DDG) from corn is used as animal feed because of its high protein content and calorific value [197]. However, the quality of DDG from fuel grade ethanol co-production differs from the quality of DDG from food grade ethanol co-production because different additives are used for each process. Therefore, differently produced DDG may have different applications, and appropriate standards must be developed to address this.

6.6 Certification and Labelling

Some of the stakeholders interviewed for this study suggested that standards, certification programs, and label ratings of carbon footprints for bio-based products would help to increase public confidence in bio-based product adoption in Canada. A bio-based content certification program could be established, similar to the European certification scheme, which is based on EN 16785-1 [198], and a carbon footprint could be quantified and reported through the adoption and possible modification of ISO 14067 [199], which is believed to help increase consumers' preference for environmentally friendly bio-based products.

Figure 3: Integrated approaches for a sustainable bioeconomy.



7. Potential Pathways Toward Sustainable Bioeconomy Standardization

7.1 Bioeconomy Complexity

The bioeconomy is a transdisciplinary, multivariate, and complex system that is not yet fully understood [102], [200]. Its stakeholders encompass extraction, production, and processing companies, service providers, consumers, organizations focused on the management of ecosystems, and investment groups [24]. As such, interdisciplinary approaches that include stakeholder participation, market development, implementation of policies, regulations, and standards, and consumer acceptance, are key for enhancing the bioeconomy and ensuring the sustainability of bio-products. One potential strategy for a smooth transition to a sustainable bioeconomy is a tripartite model that includes (a) consumer heterogeneity, (b) retailer engagement, and (c) tighter control over the quality of products [201].

A simplified, integrated approach for a sustainable bioeconomy is shown in Figure 3 and includes relationships among stakeholders at both the national and international levels. Safety, quality, sustainability, and markets for bio-based products are central pillars of a successful bioeconomy that affect and require the contribution of all parties. For example, when considering bio-product quality at the intercept between primary producers, distributors, and retailers and secondary producers, end-users/consumers, quality affects motivation and purchasing decisions. Consumers' motivation to purchase opens the door for producing higher quality products, which could lead to wider market acceptance and heightened competitiveness. However, quality of

products is also affected by regulations, policies, and standards. Therefore, at the intercept between primary producers, distributors, and retailers and government, policymakers, and regulators lays the government decision to regulate and enforce standards, while the development of standards will be dictated by industry's readiness and willingness to engage in the production of bio-based products. Similarly, standards and regulations mandating quality products can incentivize consumers' purchasing decisions, which can also affect policies and regulations. Consequently, all bioeconomy stakeholders should be consulted in the development of product-specific standards that meet the requirements of primary and secondary producers and end-users/consumers, while ensuring the safety, sustainability, and markets for the bio-based product.

In line with the relationships shown in Figure 3, public policies must create demand and competitive markets and must promote renewable options while reducing financial barriers for bio-based industries [102], [200]. A combination of policies has been shown to be more effective than a single policy, in conjunction with education that encompasses the formal and informal lessons learned from experienced stakeholders to increase awareness and to advance the competence of a skilled workforce [102].

Canada's Clean Technology Table, an industry-government collaboration, was tasked with planning for a long-term, innovation-led growth of the clean economy, including renewable energy, and proposed the following six key elements to advance the sector:

1. Regulations
2. Accelerated growth
3. Procurement
4. Partnerships and co-development
5. Global markets
6. Jobs and skills development [12]

Specific proposals included developing performance-based regulations and referencing technical standards to ensure market relevance, reducing regulatory burdens, and streamlining and accelerating regulatory exemptions or harmonization pathways. They also suggested creating an Office of Regulatory Innovation and an Innovative Regulations Advisory Council [12].

Stakeholders consulted for this report noted that the development of bio-clusters (groups of companies that use biomass at different levels) is an important policy topic for bio-based materials or lower value bio-based products. The importance of policy was also highlighted in a meta-analysis of bio-clusters that linked poor economic performance to "discrepancy of political intentions, lack of coordination, and opposite expectations at different governmental levels" [202, pp. 10]. In Canada, however, the importance of cluster planning and development at the federal level is exemplified by the cluster projects developed by Innovation, Science and Economic Development Canada [203]. For example, Bioindustrial Innovation Canada, a government-funded, non-profit organization, played an important role in diversification of the Sarnia-Lambton Hybrid Chemistry Cluster, which was initially established through the collaboration of members of the traditional petrochemical industry [204]. It currently comprises more than 35 interrelated traditional and bio-based chemical facilities producing biofuels, bio-based materials, and renewable chemicals [205]. It is anticipated that these Canadian national bio-cluster initiatives will eventually result in the development of a national framework [204].

7.2 Bioeconomy Roadmap

Policies, regulations, and standards for emerging bio-based products should be developed and regularly updated to adapt to emerging trends in the bioeconomy and to create a pathway for broader adoption of the new products and technologies. Although numerous efforts are underway to advance the Canadian bioeconomy, there is still a need to align bioeconomy initiatives through a bioeconomy roadmap that outlines the regulations and standards required to meet the strategic goals of environmental, economic, and social sustainability. Various modelling approaches can be used to create a bioeconomy roadmap. Existing frameworks, which usually analyze climate change, circularity, and, to a lesser degree, biodiversity, can be modified to include societal and technological changes [206]. For example, agent-based modelling, a computer simulation used to study the interactions between components (agents) of a system to predict outcomes, has been suggested as a way to improve and complement existing bioeconomy modelling efforts

[206]. A broad model that includes environmental, economic, and social sustainability checks would help to address and prevent any rebound effects from bio-based products, particularly with respect to impacts on the carbon life cycle and on water.

8. Discussion

8.1 Bioeconomy Sustainability Criteria

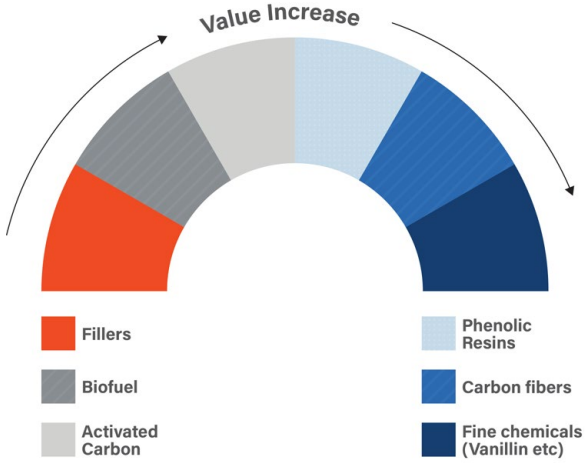
To enhance the Canadian bioeconomy and to attract and retain stakeholders, there is a need for government support, local production of technologies, skilled operators, community engagement, and evidence of socioeconomic and environmental benefits of the bio-based industry. One study on the technological development and policy measures required to improve circularity in Canada suggested that a government-created roadmap and clear policy direction at the national level could accelerate the implementation of a circular economy across and within various sectors in Canada [207]. Biotechnological advances can also play an important role in enhancing the bioeconomy by easing the transition process and by developing innovative products [208], [209].

For a sustainable bioeconomy, the production of bio-based products must be economically and environmentally sustainable while ensuring products meet quality, safety, and performance standards at a competitive price with their counterparts, as well as providing profitability to bioindustries. Sustainability requires the sustainability of base resources, processes, and products, material circularity, and consumers' acceptance of bio-based products [8]. The profitability and markets for bio-based products, including emerging and advanced products, along with the inputs in their production processes, must be considered when outlining a sustainable bioeconomy roadmap.

The prices of bio-based products and feedstock vary widely [210], in part because of tight relationships among markets, along with environmental, economic and social factors, policies, regulations, and standards. For example, this variation can be affected by method of processing, as in the case of sewage sludge management. While composting requires low investment compared to other processing technologies (pyrolysis, incineration, or anaerobic digestion), pyrolysis generates higher profits and emerges as

Figure 4: Value of lignin-based products.

Note. *Adapted with permission from [194]; License no. 5394160678404; Copyright: Elsevier, 2021.*



both the economically and environmentally preferable option [211]. Another example is variability due to end-product use, as seen with lignin, which can be used for a range of products whose prices appear to be governed by their life cycle, as shown in Figure 4 [194].

In addition to cost, bioeconomy sustainability is also affected by GHG emissions throughout the life cycle of a bio-based product, expressed as CO2-equivalent (CO2-eq) per product unit. The environmental impact of products varies widely, depending on processing technologies, feedstock, and system boundaries, as shown in Table 2.

8.2 Bioeconomy Components and Relationships

Organizations use different models to depict the diversity of bio-based products and the multidisciplinary nature of the bioeconomy. As shown in Figure 5, BioTalent Canada's model presents an array of bio-based products categorized by sub-sector (agri-bio, bio-industrial, bio-energy, and bio-health), that are based on scientific research and development, relate to the green economy and sustainable development, and share the ultimate goal of commercialization [217].

The complex structure of the bioeconomy has been studied using systems analysis and system dynamics models [200], [218]. Technology and

Table 2: Greenhouse Gas Emissions of Certain Bio-Based Products

Bio-based product	Greenhouse gas emissions	Reference
Biochar	-70 to 160 kg CO_2 eq/dry tonne of biochar	**[212]**
Yard and food waste compost	0.2 to 0.9 t CO_2 eq/t of fresh matter food waste	**[213]**
Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) and polymers reinforced with textile fibres	-4500 to 6000 kg $CO2_2$ eq/m3 of polymer	**[214]**
Pulp	408 to 513 kg CO_2 eq/t of pulp	**[215]**
Paper	951 kg CO_2 eq/t of paper	**[215]**
Wood cement composite panels	-39 to 600 kg CO_2 eq/m^3 of panel	**[216]**

innovation, market organization, resource availability, pressure on ecosystems, consumer preference, policy and regulation, and relations within the bioeconomy have been discussed as driving forces and relationships within the bioeconomy [200]. Thus, various conceptual models have been proposed for a sustainable bioeconomy [219]–[221]. These drivers coincide with success criteria for decarbonization technologies. A study of CCS projects in the United States identified technological readiness, capital cost, credibility of revenues and incentives, and regulatory challenges as important attributes for success [222]. In another study, technological progress, policy development, and market were identified as key to CCS viability in coal power generation [3].

Technologies

The issue of technological readiness for various bioeconomy process is illustrated in Figure 2. Self-reliance should also be emphasized for the development of a country's sustainable bioeconomy. For example, although bioenergy plants are operating successfully in certain remote communities in Canada, some rely on significant technical support from European manufacturers [223].

Resource Availability

Feedstock supply is expected to change with fluctuations in demand for resources, as well as with policy and regulatory changes. For example, a model developed for China's feedstock to meet 2060 carbon neutrality projected that most feedstock would consist of cellulosic crops (43%–47%) and the rest would be from biomass residues (49%–52%), which would result in cropland in China decreasing by 6.9%–8.3% [224]. The cultivation of energy crops or afforestation of marginal land to meet demand must be done carefully to avoid any rebound effects from changes to land usage. For example, afforestation in tropical regions such as those in Africa and Oceania may exacerbate water scarcity of already dry soil [225].

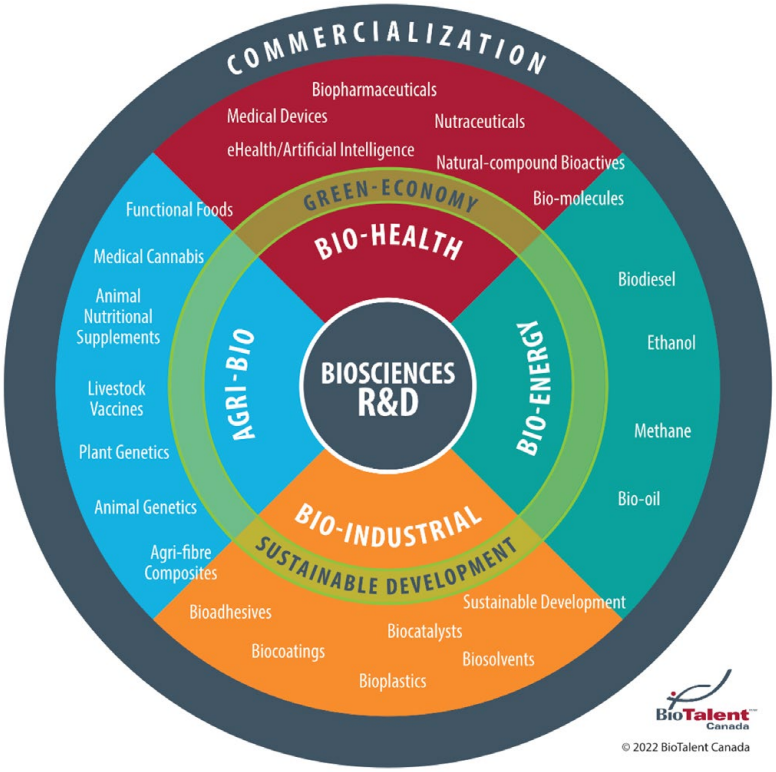
Market Organization

The international market structure of feedstock and bio-based materials is also expected to change. For example, demand for wood chips is rising in China because of the expansion of pulp industries and the lack of domestic wood fibres [226]. In contrast, the demand for wood chips in Canada is decreasing because of dwindling pulp and paper industries [227]. Consequently, Canada needs to develop alternate applications for wood chips, such as BECCS, which means that regulations and standards must be developed for these potential markets. Furthermore, Canada has announced plans to invest $81.5 million in research and development projects that support CCS and utilization [228].

Policy and Regulation

Policy and regulatory changes, along with effective standards, are essential for the sustainability of the bioeconomy. An effective governance framework for a sustainable bioeconomy requires both enabling

Figure 5: Multisectoral approach for sustainable bioeconomy in Canada.
Note. Reproduced with permission from BioTalent Canada [217].



governance (supporting measures) and constraining governance (regulatory tools), which are only effective when aligned with monitoring and assessment of activities, a lack of which can lead to over- or under-regulation of the bioeconomy [219]. Ensuring the effectiveness of policies is difficult without appropriate measurement of the bioeconomy, which can be done in different ways. The most common measure for the bioeconomy, contributions to the economy, employment, and consumption, must be accompanied by other indicators, such as the emergence of key technologies and bioeconomy innovations (patents and investments), as well as contributions to environmental sustainability and societal well-being [229]. In the United States, the bioeconomy's marginal status was attributed to a lack of awareness and lack of implementation of federal mandates, investment in biofuels to eclipse interest or investment in other bio-based industries, and uneven stakeholder power and interest, so a governance model based on regions, innovation, and collaborative efforts was suggested [230].

9. Conclusions and Recommendations

Growing concerns around climate change have led to the initiation of different activities to mitigate environmental impacts and enhance the bioeconomy. Policies, regulations, and standards can play a key role in creating a competitive market for bio-based products and in improving their economic, environmental, and social sustainability. Standards for bio-based products must consider their safety, marketability, sustainability, and compliance with bioeconomy initiatives, while addressing emerging issues and mitigating potential rebound effects. A joint effort that comprises all the relevant bioeconomy stakeholders, both national and international, is key for developing appropriate policies, regulations, and standards, especially for emerging bio-based products. Finally, a broader sustainability check must be adopted for the development and implementation of any policy, regulation, or standard in order to reduce risks to investments, minimize negative impacts to the environment, and prevent rebound effects on society.

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Appendix A1 – Definitions

Table A1: Terms and Definitions

Term	Definition	Source
bio-based	derived from biomass	CEN EN 16575 [231]
bio-based carbon	carbon derived from biomass	CEN EN 16575 [231]
bio-based chemicals	chemical products that are wholly or partly derived from materials of biological origin (e.g., biomasses, feedstock, plants, algae, crops, trees, marine organisms and biological waste)	ISO 14030-3 [232]
bio-based composites	composite material where at least one of the constituents is derived from biomass origin	CEN EN 17228 [233]
bio-based materials	material wholly or partly derived from biomass	BSI PAS 600 [234]
bio-based plastic	plastic in which constitutional units are totally or in part from biomass origin	BSI PAS 600 [234]
bio-based polymer Yard and food waste composting	polymer in which constitutional units are totally or in part from biomass origin **NOTE 1:** Bio-based polymers are not identical to bio-polymers. Bio-based polymers can be made synthetically from monomers derived from biomass, while bio-polymers are made entirely by the living organisms. **NOTE 2:** Bio-polymers can be of animal (such as collagen, chitin or spider silk), plant (such as starch and cellulose), algal (alginates) or bacterial origin (polyhydroxyalcanoates). An example of a synthetic bio-based polymer is polylactadie, produced from lactic acid. **NOTE 3:** A bio-based polymer similar to a petrochemically based one does not imply any superiority with respect to the environment unless the comparison of respective life cycle assessments is favourable.	BSI PAS 600 [234]
	bio-based synthetic polymer is polymer obtained through chemical and/or biological industrial process(es), wholly or partly from biomass resources **Note 1 to entry:** Natural polymers are not classified as biobased synthetic polymers ***natural polymer*** *is polymer obtained from biomass, in which the polymer retains the original chemical structure and composition present in biomass (EXAMPLE: Starch, cellulose, lignin, or lignocellulose)*	ISO 16620-1 [235]
bio-based products	product wholly or partly derived from biomass	CEN EN 16575 [231]
biochar	see biocoal	
biocoal	solid biofuel derived from carbonization, distillation or pyrolysis of biomass (also known as: charcoal, biochar, biocarbon, biocoke)	ISO 16559 [236]

Term	Definition	Source
bioenergy	energy derived from biomass	ISO 16559 [236]
biofertilizer	biological products containing living microorganisms that, when applied to seed, plant surfaces, or soil, promote growth by several mechanisms such as increasing the supply of nutrients, increasing root biomass or root area and increasing nutrient uptake capacity of the plant	Vessey, 2003 [237]
biofuel	solid, liquid or gaseous fuel produced directly or indirectly from biomass	ISO 16559 [236]
biogas	gas produced by anaerobic digestion of organic matter, gasification of biomass or power to gas from biomass sources and without further upgrading or purification	ISO 20675 [238]
bioheat	thermal energy produced from biomass, used either for space heating or in production processes requiring process heat such as steam, generally via combustion of the feedstock or a derived product (e.g., biogass). Bioheat is often, though not always, co-generated with biopower	OECD, 2010 [239]
biomass	material of biological origin excluding material embedded in geological formations and/or fossilized **Note 1 to entry:** Biomass is organic material that is plant-based or animal-based, including, but not limited to dedicated energy crops, agricultural crops and trees, food, feed and fibre crop residues, aquatic plants, alga, forestry and wood residues, organic agricultural, animal and processing by-products, agricultural, municipal and industrial organic waste and residues whether or not in landfills, sludge, waste water, and other non-fossil organic matter	ISO 20675 [238]
biopower	electricity produced from biomass, generally via combustion of the feed-stock or a derived product (e.g., biogas) driving power generating turbines. Biopower is often, though not always, co-generated with bioheat	OECD, 2010 [239]
biosolids	organic-based materials from industrial or municipal wastewater sludge and their derived products, in the form of solids, semi-solids, semi-liquids (pasty), and liquids which have been treated to meet specific standards, guidelines or requirements including the reduction of pathogens, vector attraction and contaminant criteria	ISO 19698 [143]
feedstock	material that is further processed for conversion to bioenergy, biofuel and/or bio-based products	ISO 16559 [236]
lignin	class of complex organic macromolecules, containing aromatic sub-units, that plays a key role in the formation of cell walls in wood and bark, conferring mechanical strength and rigidity to the cell walls and to plants as a whole **Note 1 to entry**: Lignin is the main non-carbohydrate constituent of wood	ISO 24215 [240]
pyrolysis	thermal treatment without supply of oxygen	ISO/TR 20736 [241]

Appendix A2 – Study Survey and Interview Questions

A2.1 Survey

The Canadian Standards Association (CSA Group) has hired Sandler Consultancy (SC) to engage stakeholders from across Canada within various sub-sectors of the bioeconomy. We would like to ascertain your opinions and perspectives on where you think gaps in standards currently exist that are affecting the safety, performance, and/or quality of the goods and services being produced within your sector of the bioeconomy. We are also interested in identifying gaps in standards that may be affecting interconnected sub-sectors. For the purposes of this survey, we are looking specifically at the following sub-sectors within resource extraction and production/refinement:

A. Resource Extraction:

- Agriculture
- Forestry
- Biowaste (municipal waste/sewage byproducts)

B. Production and Refinement:

- Bio-based chemicals
- Biofuel
- Bioenergy
- Bio-based material

The opinions and data gathered from this survey will be anonymously used in the publication produced by CSA Group to guide the development of future standardization solutions.

Our research to date indicates that you are an informed stakeholder within the bioeconomy, and we would greatly appreciate your input.

We also hope to follow up with you to have a more in-depth discussion with one of our researchers. Would you be willing to participate in a short interview regarding Bioeconomy Standardization? YES / NO or [Type Your Answer]

Thank you. Please provide your preferred email address and one of our researchers will be in touch.

Questions

Q: Within which of the following bioeconomy subsectors do you currently work?

- Agriculture
- Bio-based chemical
- Bioenergy
- Biofuel
- Bio-based material
- Biowaste
- Forestry
- Other [Type Your Answer]

Q: How many years in total have you worked in one or more of the following subsectors?

0-1	Agriculture_____	Biofuel_____
1-5	Forestry_____	Bioenergy_____
6-10	Biowaste_____	Bio-based material_____
10+	Bio-based chemical_____	Other [Type Your Answer] _____

Q: Which of the following best describes your current role?

- Founder/Entrepreneur
- Harvester
- Producer
- Researcher/Scientist/Engineer
- Technologist
- Manufacturer
- Sales/Marketing
- Regulator
- Other [Type Your Answer]_____

Q: How is your organization classified?

- Public Sector (Regional)
- Public Sector (Federal)
- Public Sector (Provincial)
- Public Sector (Municipal)
- Private
- Not-for-Profit

Q: In which geographical regions do you conduct business (buy/sell/service)**?**

- Within Canada – Please specify Province and/or Municipality.
- Within the United States – Please specify State and/or Municipality.
- Internationally – Please specify Country, State and/or Municipality.

Q: Where does your organization go to look for Standards, Codes or Regulations that are relevant for your work?

Q: Are there specific Codes, Standards and/or Regulations that are currently being used by your organization? If so, please provide examples.

Q: Please rank the importance of the following categories of Bioeconomy Standards to your industry:

- Quality
- Performance
- Safety

Q: Please rank the importance of the following Standards in the bioeconomy value chain applicable to your industry: 1 being the highest impact and 7 being the lowest.

- Raw Material (Characteristics, Specifications)
- Processing & Manufacturing
- Products (e.g., Biofuels, bio-based chemicals, etc.)
- Storage & Transportation
- End-use Applications (Installation, Performance)
- End-of-Life Management (i.e., Recycling)
- Other [Type Your Answer]_____

Q: Please elaborate on whether any of the standards listed in the previous question are impacting your organization's ability to participate in the bioeconomy by listing the top three standards and their impact? Note: Listed standards include raw material, processing & manufacturing, products, storage & transportation, end-use applications, end-of-life management).

Q: If applicable, please list any products your organization is producing that require existing and new standards in the bioeconomy value chain applicable to your industry.

Q: Considering the categories listed in the previous questions, what additional standards, codes, guidelines, test methods and or product specifications need to be developed relating to the quality, performance or safety of products within your sector of the bioeconomy?

Q: If you are involved in regulatory or advocacy work what type of standards or new guidelines would you like to see introduced to improve the success of your regulatory or advocacy work?

Q: If you are developing a new product/service, what type of bio-specific standards would you like to see further developed or newly created to improve the success of your offering?

Q: Please select the top three of the following initiatives that would have the most impact on improving Canada's bioeconomy:

- Imposing restrictive regulations against fossil fuel-based products
- Providing more incentives for production/consumption of bio-based products
- Referencing quality/safety/performance standards and guidelines in regulations
- Certification programs based on the developed standards
- Producing higher-quality crops
- Filling gaps in the supply chain
- Larger end-user market
- Other [Type Your Answer]_____

Q: If applicable, please describe how you use the terms below in your professional role:

- Circular Economy
- Life Cycle Assessment
- Net Zero Economy

Thank You! We appreciate you taking the time to complete this survey.

A2.2 Interview Questions

Table A2: Follow-up Questions for Direct Engagement Interviews

Organization/Business	Questions
Academic/Policymaker	1. Are you aware of any changes to or introduction of new standards that could enhance the sector(s) of the bioeconomy that you work in? 2. What constraints do you foresee impacting the introduction of new standards? 3. How would the new standards improve the prospects for the specific sector of the bioeconomy that you work in? 4. Do you expect any rebound or negative effects from the introduction of these suggested standards? 5. How can these rebound effects be overcome?
Biomass Producer	1. What type of biomass do you produce? 2. What constraints are you facing with respect to standards and or guidelines impacting your production processes? 3. Can you give any examples of new standards - or changes that could reduce the constraints you are facing?
Bioproduct Producer/ Investor	1. What regulations/standards is your organization using? 2. Are there any constraints that you are facing with these standards? If so, what are they? 3. Are there changes to existing standards, or would the introduction of new standards improve the efficiency or profitability of your business? 4. Is there a market for your bioproduct(s) in Canada? If so, are there additional standards that can assist with enhancing your market penetration?
Business (Distributor/ Retailers /Exporter/ Importer)	1. What bio-products do you sell? 2. Do you face problems with these products that could be reduced or eliminated by the adherence to new standards or guidelines for quality, performance or safety? Do you have any suggestions of what these new standards or guidelines could be? 3. How would new guidelines or standards solve issues for the sale of your products?
Secondary User/End User	1. What criteria do you consider for selecting a bioproduct? 2. Are there any concerns about the products you use? 3. What kind of standards or guidelines would you want to see introduced to address your concerns?

Appendix A3 – Examples of Bioeconomy Standards and Topics

Table A3: Examples of bioeconomy standards and topics

Topic	Standard designation	Standard title	Reference
Environmental stewardship	RSB Standard	Roundtable on sustainable biomaterials	[65]
Biomass supply chain risk	CSA W209	Biomass supply chain risk	[242]
Biodiesel	CAN/CGSB-3.524	Biodiesel (B100) for blending in middle distillate fuels	[243]
Biochar	IBI-STD-2.1	Standardized product definition and product testing guidelines for biochar that is used in soil	[244]
Kraft lignin	CSA W206	Kraft lignin – Glass transition temperature by differential scanning calorimetry	[245]
Kraft lignin	CSA W207	Kraft lignin – Determination of thermal stability by thermogravimetry	[246]
Lignin	ISO 24196	Lignins – Determination of lignin content in kraft lignin, soda lignin and hydrolysis lignin	[247]
Lignin	ISO 24215	Lignins – Determination of carbohydrate composition in kraft lignin, soda lignin and hydrolysis lignin	[240]
Lignin	ISO/DIS 9795 (under development)	Lignins – Determination of inorganics content in kraft lignin, soda lignin and hydrolysis lignin	[248]
Lignin	CSA W213	Lignin – Quantification of hydroxyl groups by 31P NMR	[190]
Pulp	ISO 21436	Pulps – Determination of lignin content – Acid hydrolysis method	[249]
Cellulose filament	CSA Z5300	Cellulose filaments (CF) – Preparing handsheets for physical tests	[250]
Cellulose fibre	CAN/ULC-S703	Standard for cellulose fibre insulation for building	[251]
Packaging material	CSA W221	End-of-life management and traceability of forest bio-based packaging materials	[252]
Bioenergy supply chain	ISO 13065	Sustainability criteria for bioenergy	[253]
Bio-based products	CEN EN 16751	Bio-based products – Sustainability criteria	[254]
Cellulose nanomaterials	CAN/CSA-Z5100	Cellulose nanomaterials – Test methods for characterization	[255]

Topic	Standard designation	Standard title	Reference
Cellulose nanomaterials	CAN/CSA-Z5200	Cellulose nanomaterials – Blank detail specification	[256]
Nanomaterials	ISO/TS 20477	Nanotechnologies – Standard terms and their definition for cellulose nanomaterial	[257]
Nanomaterials	ISO 2144	Paper, board, pulps and cellulose nanomaterials – Determination of residue (ash content) on ignition at 900 °C	[258]
Solid biofuels	CSA ISO 17225-1	Solid biofuels – Fuel specifications and classes – Part 1: General requirements	[259]
Wood chips	CSA O302.1/O302.2	Scaling roundwood/Measurement of wood chips, tree residues, and byproducts	[260]
Solid biofuels	CSA ISO 17225-2	Solid biofuels – Fuel specifications and classes – Part 2: Graded wood pellets	[261]
Solid biofuels	CSA ISO 17225-3	Solid biofuels – Fuel specifications and classes – Part 3: Graded wood briquettes	[262]
Solid biofuels	CSA ISO 17225-4	Solid biofuels – Fuel specifications and classes – Part 4: Graded wood chips	[263]
Solid biofuels	CSA ISO 17225-5	Solid biofuels – Fuel specifications and classes – Part 5: Graded firewood	[264]
Solid biofuels	CSA ISO 17225-6	Solid biofuels – Fuel specifications and classes – Part 6: Graded non-woody pellets	[265]
Solid biofuels	CSA ISO 17225-7	Solid biofuels – Fuel specifications and classes – Part 7: Graded non-woody briquettes	[266]
Solid biofuels	CAN/CSA ISO 16559	Solid biofuels – Terminology, definitions and descriptions	[236]
Solid biofuels	CSA ISO 17830	Solid biofuels – Particle size distribution of disintegrated pellets	[267]
Solid biofuels	CAN/CSA ISO 18846	Solid biofuels – Determination of fines content in samples of pellets	[268]
Solid biofuels	CSA ISO 16993	Solid biofuels – Conversion of analytical results from one basis to another	[269]
Solid biofuels	CSA ISO 16994	Solid biofuels – Determination of total content of sulfur and chlorine	[270]
Solid biofuels	CSA ISO 18847	Solid biofuels – Determination of particle density of pellets and briquettes	[271]

Topic	Standard designation	Standard title	Reference
Solid biofuels	CSA ISO 20023	Solid biofuels – Safety of solid biofuel pellets – Safe handling and storage of wood pellets in residential and other small-scale applications	[272]
Solid biofuels	CSA ISO 20024	Solid biofuels – Safe handling and storage of solid biofuel pellets in commercial and industrial applications	[273]
Solid biofuels	CSA ISO 21945	Solid biofuels – Simplified sampling method for small scale applications	[274]
Forest stewardship	FSC-STD-60-006	Process requirements for the development and maintenance of national forest stewardship standards	[275]
Forest stewardship	FSC-PRO-60-007	Structure, content and development of interim national standards	[276]
Forest stewardship	FSC-GUI-60-002	Guideline for standard developers for addressing risk of unacceptable activities in regard to scale and intensity	[277]
Forest stewardship	SFI 2022	SFI Forest management standard	[67]
Forest stewardship	SFI 2022	SFI Fiber sourcing standard	[67]
Biosolids	CAN/BNQ 0413-400	Soil amendments – Alkaline or dried municipal biosolids	[165]
Organic agriculture	CAN/CGSB-32.310	Organic production systems – General principles and management standards	[167]
Organic production systems (agriculture)	CAN/CGSB-32.311	Organic production systems – Permitted substances lists	[278]
Organic production systems (aquaculture)	CAN/CGSB-32.312	Organic production systems – Aquaculture – General principles, management standards and permitted substances lists	[279]
Digestate	BSI PAS 110	Specification for whole digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials	[280]
Composts	CAN/BNQ 0413-220	Organic soil conditioners – Composts – Determination of respiration rate – Part I: Respirometric method – Part II: Modified biochemical oxygen demand (BOD) respiration method	[281]
Composts	CAN/BNQ 0413-210	Organic soil conditioners – Composts – Determination of foreign matter content – Sieving method	[282]
Composts	CAN/BNQ 0413-200	Organic soil conditioners – Composts	[166]

Topic	Standard designation	Standard title	Reference
Environmental protection	ISO 14065	General principles and requirements for bodies validating and verifying environmental information	[283]
Environmental protection	ISO 14064-1	Greenhouse gases – Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals	[284]
Environmental protection	ISO 14064-2	Greenhouse gases – Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements	[285]
Environmental protection	ISO 14064-3	Greenhouse gases – Part 3: Specification with guidance for the verification and validation of greenhouse gas statements	[286]
Environmental protection	ISO 14066	Greenhouse gases – Competence requirements for greenhouse gas validation teams and verification teams	[287]
Carbon capture and storage	CSA Z741	Geological storage of carbon dioxide	[288]
Carbon capture and storage	ISO 27917	Carbon dioxide capture, transportation and geological storage – Vocabulary – Cross cutting terms	[289]
Carbon capture and storage	ISO 27914	Carbon dioxide capture, transportation and geological storage – Geological storage	[290]

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.

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