UN environment programme

Global Bioeconomy Assessment

Coordinated Efforts of Policy, Innovation, and Sustainability for a Greener Future

© 2024 United Nations Environment Programme

ISBN:	978-92-807-4142-1
Job number:	DEP/2632/NA
DOI:	https://doi.org/10.59117/20.500.11822/45332

This publication may be reproduced in whole or in part and in any form for educational or non-profit services without special permission from the copyright holder, provided acknowledgement of the source is made. The United Nations Environment Programme would appreciate receiving a copy of any publication that uses this publication as a source. No use of this publication may be made for resale or any other commercial purpose whatsoever without prior permission in writing from the United Nations Environment Programme. Applications for such permission, with a statement of the purpose and extent of the reproduction, should be addressed to unep-communication-director@un.org.

Disclaimers

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory or city or area or its authorities, or concerning the delimitation of its frontiers or boundaries.

Mention of a commercial company or product in this document does not imply endorsement by the United Nations Environment Programme or the authors. The use of information from this document for publicity or advertising is not permitted. Trademark names and symbols are used in an editorial fashion with no intention on infringement of trademark or copyright laws.

The views expressed in this publication are those of the authors and do not necessarily reflect the views of the United Nations Environment Programme. We regret any errors or omissions that may have been unwittingly made.

© Maps, photos and illustrations as specified

Suggested citation

United Nations Environment Programme (2024). Global Bioeconomy Assessment: Coordinated Efforts of Policy, Innovation, and Sustainability for a Greener Future. Nairobi. https://doi.org/10.59117/20.500.11822/45332

Production: Nairobi, Kenya.

URL: https://wedocs.unep.org/20.500.11822/45332

Acknowledgements

The United Nations Environment Programme (UNEP) would like to thank the authors and the project coordination team for their contribution to the development of this report. Authors and reviewers have contributed in their individual capacities. Their affiliations are only mentioned for identification purposes.

Authors

Yutao Wang (Fudan University [FDU])

Mingxing Sun (Institute of Geographical Sciences and Natural Resources Research [IGSNRR], Chinese Academy of Sciences [CAS]/UNEP-International Ecosystem Management Partnership [UNEP-IEMP])

Linxiu Zhang (UNEP-IEMP)

Reviewers (listed in alphabetic order)

Anthony Shun Fung Chiu
(De La Salle University, Manila, Philippines)

Bakhita Amondi Oduor
(Ecosystem Division, UNEP)

Bavelyne Mibei
(Policy and Programme Division, UNEP)

Cecilia M. V. B. Almeida
(Universidade Paulista, Brazil)

Jane Muriithi
(Early Warning and Assessment Division, UNEP)

Jiashuo Li
(Shandong University, China)

Jing Meng
(University College of London, United Kingdom)

Mingzhou Jin
(The University of Tennessee, USA)

Raymond Brandes
(Policy and Programme Division, UNEP)

Secretariat and project coordination

Mingxing Sun (IGSNRR, CAS/UNEP-IEMP)
Yutao Wang (FDU)
Linxiu Zhang (UNEP-IEMP)
Chao Fu (IGSNRR, CAS/UNEP-IEMP)

Language editing

Strategic Agenda (Xain Storey, Liyana Aini)

Design and layout

Strategic Agenda

Thanks also to:

Huajun Yu (FDU), Bin Chen (FDU), Sijing Wang (FDU), Meili Xue (FDU), Huijing Deng (FDU), Ju Wang (FDU), Xinyi Long (FDU), Dingfan Zhang (FDU), Lin Sun (FDU), Zhixiu Han (FDU), Hongyi Xie (FDU), Yingfan Duan (FDU), Jingjing Zhang (FDU), Yixiang Gao (FDU), Juezhu Chen (FDU), Yixuan Bai (FDU), Yiru Song (FDU), Shiwen Gong (FDU).

Financial and technical support

This knowledge product is prepared in the context of the “Global Biomass Resource Sustainability and Climate Change Adaptation Management” project funded by the National Natural Science Foundation of China (72061147003).

Acronyms and abbreviations

ASTM	American Society of Testing Materials
ATJ	Alcohol-to-jet
BMBF	Federal Ministry of Education and Research
EGD	European Green Deal
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FDCA	2,5-Furandicarboxylic acid
FT	Fischer-Tropsch
GHG	Greenhouse gas
HEFA	Hydroprocessed esters and fatty acids
HEFA-SPK	Hydroprocessed ester and fatty acids synthetic paraffinic kerosene
HMF	5-Hydroxymethylfurfural
ILUC	Indirect land-use change
LAC	Latin America and Caribbean
OECD	Organisation for Economic Co-operation and Development
PA	Polyamide
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PHA	Polyhydroxyalkanoates
PLA	Polylactic acid
PP	Polypropylene
PPI	Printing and publishing industry
PTA	Terephthalic acid
PTT	Polytrimethylene terephthalate
RED	Renewable Energy Directive
RME	Rapeseed methyl ester
SDG	Sustainable Development Goal
SIP	Synthesized iso-paraffins
USA	United States of America

Table of contents

List of tables

List of figures

Executive summary

The bioeconomy, also known as the bio-based economy, refers to the economic activity involving the use of biotechnology and biomass in producing goods, services or energy. It aims to reduce the dependence on fossil fuels in the energy and industrial sectors. Bioeconomy has been widely accepted by different countries and regions as a critical strategy for coping with fossil fuel shortage and climate change, among other environmental problems. Bioeconomy mainly utilizes biomass resources to generate bio-based products. In terms of biomass resources, they can be divided into three generations. The first-generation biomass resources, primarily edible biomass materials, present an issue of "competing with people for food/land." The second-generation biomass resources are derived from non-edible sources, mainly lignocellulosic materials, which are accompanied by immature processes for their efficient conversion into valuable biofuels and other high-value bioproducts. Third-generation biomass resources represent an emerging frontier in the world of sustainable bioenergy and bioproducts, primarily consisting of algae or rapidly synthesized biomass achieved through advanced cell engineering techniques. According to the utilization methods, bio-based products can be divided into five categories: energy, raw material, feed, base material and fertilizer. Specifically, energy use is the most universal type of utilization, and biomass energy utilization forms include solid fuel, liquid fuel and gas fuel. There are also many ways to use raw materials, such as bio-based chemicals, bio-based plastics and macromolecular materials. This report focuses on bioenergy, bio-based chemicals, bio-based plastics and bio-based macromolecular materials (textiles and paper) in technical conversion, highlighting the resources, dominating technical routes, challenges and prospects.

To promote bioeconomy, many countries have put forward diverse strategies. Throughout history, the United States of America (USA) took an early lead in bioeconomic strategy and policy, exemplified in 1999 by the issuance of the Executive Order 13134, titled "Developing and Promoting Biobased Products and Bioenergy". Following suit, the European Union (EU) swiftly released key policy documents in 2005, 2007 and 2010, including "Bioeconomy in Europe: Achievements and Challenges", emphasizing the central role of knowledge in the bioeconomy. After that, multiple policies have been issued, including the EU Bioeconomy Strategy in 2018 and the European Green Deal in 2019. Developing countries joined the bioeconomy movement. These policy documents delve deeper into the critical role of knowledge in the bioeconomy. In 2013, Malaysia introduced its "Bioeconomy Transformation Program," signifying the recognition of the strategic importance of the bioeconomy in Asian developing nations. China advanced its bioeconomy development though five-year plans and specific policies on renewable energy development and non-food materials utilization. During the same period, South Africa unveiled its "Bioeconomy Strategy". Among developing countries, besides resource-rich nations which have formulated national bioeconomy strategies, over 30 countries have designed bioeconomic policies for specific sectors or domains. These emerging global bioeconomy policy trends incorporate life cycle carbon disclosure, trade, digital transformation and carbon pricing and carbon credits into the framework.

The bioeconomy, driven by the sustainable development of biological resources, impacts land-use patterns and biodiversity. The demand for bio-based products and biofuels is changing land-use practices and agriculture, as they can compete with food production and affect natural ecosystems. To ensure sustainability, sustainable practices, regulatory frameworks and careful land-use planning are necessary, measures to mitigate the adverse effects on biodiversity should be taken, such as responsible land planning and eco-friendly pesticides. Biodiversity protection and the bioeconomy can coexist and offer business opportunities, promoting economic growth and developing bio-based products. To achieve a sustainable bioeconomy and biodiversity conservation, practices that mitigate the negative impacts of economic development on biodiversity should be adopted. This includes improving land-use efficiency, reducing fertilizer use, avoiding large-scale deforestation and promoting other ecosystem services. Emphasizing the synergistic development of the economy and ecology can provide sustainable conditions for the bio-based economy and human survival.

Bio-based products and bioenergy offer climate mitigation benefits in various industries, replacing non-renewable materials and fossil fuels while utilizing waste biomass. However, their climate impacts vary and are influenced by factors like feedstock source and product lifetime. Future efforts should focus on increasing long-lived bioproducts and waste biomass utilization to improve climate benefits. The bioeconomy's sustainability may be threatened by sudden-event and slow-onset climate risks. Sudden events, such as hurricanes, floods, droughts and wildfires, have immediate and severe consequences on agriculture, forestry and fisheries, leading to biomass resource scarcity, damaged agricultural infrastructure and disrupted ecosystems. Slow-onset impacts, such as shifts in precipitation patterns and rising temperatures, alter crop growth, planting seasons and increase pest and disease risks, affecting fish distribution and forest growth cycles. Addressing these impacts is crucial for sustainable bioresource management in the face of climate change.

1

Introduction

1.1 The concept and definition of bioeconomy

The bioeconomy, also known as the bio-based economy, is built on the research, development and application of life sciences and biotechnology. Its development aims to reduce dependence on fossil fuels in all sectors. As the global population grows and the available arable land per capita decreases, food scarcity is one of the main issues driving the development of the bio-based economy (Ladu and Quitzow 2017). Under the pressure of population growth and increasing food demand, the application of biotechnology can significantly increase crop yields and improve the nutritional quality of food. The emergence of the bioeconomy contributes to global economic growth and aligns with human needs for health, environmental sustainability, climate change mitigation and well-being beyond material comforts (Wang 2004; Philp 2018). Given the increasing pressures on resources and the environment, industrial development must adopt a new path characterized by low resource consumption, low pollutant emissions, high efficiency and high circularity. This includes the development of bioenergy, such as the production of bioethanol, biodiesel, bioelectricity, biohydrogen and other bioenergy sources as partial substitutes for depleting fossil fuels, thereby increasing the world's energy sustainability and security.

The bioeconomy has been attracting more and more attention from the academic community worldwide. However, there still needs to be a precise, scientific and unified definition of what the bioeconomy is. The development of life sciences and biotechnology has played a crucial role in shaping and advancing the concept of the bioeconomy. In 1998, Juan Enriquez pointed out that discoveries and applications in genomics and other fields would lead to a molecular-genetic revolution. This revolution would result in the reorganization and integration of health care, agriculture, food, nutrition, energy and the environment, ultimately leading to profound changes in the global economy (Enriquez 1998). A significant milestone in the development of the bioeconomy concept came with the issuance of Executive Order 13134, which marked the introduction of the concept and initiatives related to the bio-based economy by the Government of the United States of America (USA).

In the year 2000, the April issue of the Shanghai *Economic Outlook* magazine published a column titled "Bioeconomy: Where the Pouring Gold Coins Land", which introduced the term bioeconomy. In May of the same year, the USA-based Time Magazine published an article titled "What Will Replace the Technology Economy", introducing bioeconomy as a concept, although it did not provide a specific definition (Davis and Meyer 2000). In November 2001, at the United Nations Conference on Trade and Development in Geneva, researchers C. Juma and V. Konde from Harvard University submitted a report titled "The New Bioeconomy". This is the earliest known paper specifically discussing the bioeconomy. The report indicated that the new bioeconomy referred to the impact of modern biotechnology and the markets it occupied but did not provide a standardized definition (Joachim 2017). In 2002, Chinese scholars conducted research and published a standardized definition stating that the bioeconomy was an economy based on the research, development and application of life sciences and biotechnology; that it was built on biotechnology products and industries and represented a new economic form corresponding to agricultural, industrial and information economies (Deng 2002). This definition comprises both core connotations and extended explanations and remains one of the earliest published standardized definitions of the bioeconomy discovered. In 2003, management professionals in the field of biotechnology in the Chinese Ministry of Science and Technology proposed a definition of the bioeconomy, stating that it was an economy built on biological resources and biotechnology foundations, with its basis in the production, distribution and utilization of biotechnological products (Wang 2004).

The standardized definition of the bioeconomy gained more momentum after the Organisation for Economic Co-operation and Development (OECD) proposed the following definition in its 2004 report titled "Biotechnology for Sustainable Growth and Development":

> **"The bioeconomy is 'an economic form that utilizes renewable biological resources, efficient biological processes, and ecological industry clusters to produce sustainable bio-based products, create employment, and generate income.'"**

Subsequently, in its official documents, OECD adjusted the definition:

> **"The bioeconomy is 'an economy built upon the utilization of biotechnology and renewable energy resources to produce ecological products and services.'" (OECD 2011).**

In 2005, the European Union (EU) characterized the bioeconomy as the "knowledge-based bioeconomy" (European Commission 2005). In subsequent strategic reports, plans and documents, the EU adjusted the concept and definition of the bioeconomy. For example, in the 2011 policy paper titled "European Bioeconomy in 2030: A Vision and Action Plan", the EU defined the bioeconomy as an economic form encompassing a range of products, including food, health, fibres, industrial products and energy, obtained through the sustainable production and conversion of biomass (European Technology Platforms 2011). In February 2012, when releasing the "Innovation for Sustainable Growth: A Bioeconomy for Europe" strategy, the EU defined the bioeconomy in its official communications as an economy that utilizes biological resources from both land and sea, as well as waste materials as inputs for industrial and energy production. This definition covers using bio-based processes in the green industrial sector (European Commission 2012).

In 2012, the USA defined the bioeconomy in the "National Bioeconomy Blueprint" as an economic form based on applying biological science research and innovation, used to create economic activities and public benefits. This definition emphasizes the leading role of research and innovation (USA, White House 2012).

The German Bioeconomy Council suggested an official definition in 2016 that is not only highly representative but also concise and comprehensive. According to the German Bioeconomy Council (2018), the bioeconomy is the sustainable and innovative use of renewable biological resources to generate food, raw materials and industrial products with improved performance.

In summary, the bioeconomy encompasses the bio-based economy and the development, utilization and production of food, feed, energy and related products. Most definitions directly or indirectly share the following common characteristics: first, the bioeconomy originates from research and development in the life sciences and biotechnology, which drive its growth. Second, it involves the production of renewable and sustainable bio-based materials, energy and products through biological processes, with renewable biomass or resources serving as a critical foundation for bioeconomy development. Third, the bioeconomy is closely associated with energy efficiency, emissions reduction, green and renewable practices, health and well-being, green product transformation and economical green transformation.

1.2 Different generations of biomass resources

As the world population grows and living standards improve, so does the demand for energy, chemicals and materials. For now, most energy, chemicals and polymers come from fossil fuels, placing great pressure on fossil fuel supply and other environmental problems, climate change being prominent. Amid the dual pressure of resource shortage and environmental issues, there is considerable interest in using natural biomass as raw materials to develop energy, chemicals, polymers and materials, as natural biomass is considered renewable and carbon-neutral. Many sustainable polymeric materials also have admirable biocompatibility, which may be advantageous in broader applications.

In the context of depleting fossil fuel resources and escalating greenhouse effects, biomass resources are the only organic carbon source in nature and have emerged as an ideal alternative to fossil fuels. Unlike fossil fuels, biomass resources are geographically distributed more evenly, offering a more secure and reliable supply chain. Domestic biomass utilization can also reduce transportation costs and create local and high-tech job opportunities.

1.2.1 First generation: balancing food and fuel

First-generation biomass resources, mainly comprising edible biomass materials like corn, sugar cane, sorghum, soybean, rapeseed oil, palm oil and other oil crops, represent a critical component of the renewable energy landscape (Ben-Iwo *et al*. 2016). These resources possess distinctive characteristics, primarily starch or oil content, which can be transformed through well-established processes into valuable biofuels like bioethanol, biodiesel and other essential biomass products (Esmaeili *et al*. 2020).

However, utilizing first-generation biomass resources presents a complex and multifaceted set of challenges (Fu *et al*. 2022). One of the most prominent issues is the inherent conflict between using these resources for food production and diverting them for energy purposes. This dilemma is often called the "competing with people for food" conundrum, as these resources serve as primary food staples for communities worldwide (Muscat 2020).

Further, there's the issue of "competing with people for land". Large-scale cultivation of first-generation biomass crops can result in land-use changes, including the deforestation and displacement of food crops, which can have adverse ecological and socioeconomic consequences (Popp *et al*. 2014). An illustrative example is the extensive deforestation in South-East Asia to make way for oil palm plantations to produce palm oil for biodiesel production in Europe (Corley 2009).

In general, utilizing first-generation biomass resources presents a complex dilemma, as their conversion into bioproducts competes with food production and can have adverse environmental consequences. Striking a balance between addressing bioproducts needs and ensuring food security is a critical challenge that governments and organizations worldwide actively should address to promote sustainable development and meet multiple United Nations Sustainable Development Goals (SDGs).

1.2.2 Second generation: unlocking the power of non-edible biomass

Second-generation biomass resources represent a significant advancement in sustainable bioenergy. Unlike their first-generation counterparts, which primarily consist of edible crops, second-generation biomass resources are derived from non-edible sources, mainly lignocellulosic materials (Mujtaba *et al*. 2023). These valuable resources encompass a wide range of materials, including agricultural and forestry wastes like crop stalks, dedicated energy crops such as switchgrass and miscanthus, urban and rural organic solid waste, waste oils and other discarded materials.

One distinguishing feature of second-generation biomass resources is their predominance in the contemporary bioenergy landscape. These resources, primarily comprising lignocellulose components – namely cellulose, hemicellulose and lignin – offer significant potential for resource utilization and energy production (Mujtaba *et al*. 2023). However, the challenge lies in developing mature processes for efficient conversion into valuable biofuels and other high-value bioproducts (Carriquiry 2011).

One notable advantage of second-generation biomass resources is their ability to address the critical issue of "competing with people for food". Since these resources are mainly agriculture and forest byproducts, they do not directly threaten food security. This key attribute has alleviated concerns about diverting food crops towards energy production, fostering a more sustainable and equitable approach to bioenergy. Nevertheless, cultivating dedicated energy crops, such as switchgrass and miscanthus, can raise the concern of "competing with people for land". As land resources are finite, there is a need for responsible land management and allocation to ensure that the cultivation of energy crops does not encroach on essential food-producing areas nor exacerbate deforestation (Monti *et al*. 2012).

In conclusion, second-generation biomass resources hold immense promise in transitioning to a sustainable and bio-based economy. Their non-edible nature eliminates the “competing with people for food” challenge plaguing first-generation biomass, while the issue of “competing with people for land” necessitates careful land-use planning and sustainable agricultural practices. As we advance our understanding of lignocellulosic conversion technologies, second-generation biomass resources play a pivotal role in mitigating climate change, reducing reliance on fossil fuels and promoting a more balanced and sustainable use of our natural resources. Second-generation biomass also emphasizes responsible forest management and the development of technologies that enable efficient biomass conversion (Naik *et al*. 2010). It highlights the importance of harnessing transformative biomass to minimize environmental impacts and maximize its contribution to a circular and sustainable economy (Velenturf and Purnell 2021).

1.2.3 Third generation: algae and advanced synthesis

Third-generation biomass resources represent an exciting frontier in sustainable bioenergy and bioproducts. These resources primarily consist of algae or rapidly synthesized biomass achieved through advanced cell engineering techniques (Thanigaivel 2022; Li *et al*. 2023). What sets third-generation biomass apart is its remarkable ability to grow rapidly and, in many cases, be tailored to synthesize specific target biomolecules (Ma *et al*. 2019). These resources do not pose the challenges of “competing with people for food” or “competing with people for land” that have plagued previous generations of biomass.

Algae, a prime example of third-generation biomass, have garnered significant attention for their potential to revolutionize bioenergy and bioproduct production. They thrive in diverse aquatic environments, including oceans, lakes and wastewater treatment facilities, and are known for their exceptionally rapid growth rates. Algae can be harnessed to produce an array of valuable products, including biofuels (such as biodiesel and bioethanol), high-value chemicals, nutritional supplements, and even pharmaceuticals (Behera *et al*. 2015).

Moreover, third-generation biomass resources often involve cutting-edge cell engineering techniques that allow for the precise control of biomass composition and the synthesis of desired molecules (Sikarwar *et al*. 2017). This level of control is a game changer in the bioenergy and bioproducts industry, as it enables the production of specific compounds for various applications.

However, it is important to note that, despite their immense potential, the commercialization and comprehensive utilization of third-generation biomass resources are still evolving. Challenges remain in optimizing cultivation and conversion processes, in ensuring economic feasibility and in scaling production to meet global demands (Ma *et al*. 2019). Nonetheless, ongoing research and innovation propel third-generation biomass resources closer to becoming a commercially viable and environmentally sustainable solution (Khan *et al*. 2018).

In conclusion, third-generation biomass resources, characterized by algae and advanced synthesis techniques, represent a promising leap forward in pursuing sustainable bioenergy and bioproducts. Their rapid growth, versatility and lack of competition with food crops or land resources position them as vital to our journey to a more sustainable and bio-based future. While commercialization challenges persist, the potential benefits of third-generation biomass make it an area of continued exploration and innovation in the field of renewable resources.

1.3 Main categories of bio-based products

Biomass resource utilization methods can be divided into five categories: energy, raw material, feed, base material and fertilizer (Wang *et al*. 2022). Energy use is the conversion (or direct utilization) of biomass resources to produce energy, such as anaerobic fermentation and direct combustion power generation. Raw material use is the conversion of biomass into non-energy products, such as furniture products, paper products, textile products and rubber. Feed use refers to biomass used to feed livestock and poultry. Base material use means that biomass is used as a substrate for fungal culture.

Fertilizer use is the direct return of biomass to the field or the return of biomass after conversion. The utilization methods covered in this report are bioenergy (energy) and bio-based products (raw materials). Energy utilization is the most widely used type of utilization. Biomass energy utilization forms include solid fuel, liquid fuel and gas fuel. There are also many ways to use raw materials, and this report mainly analyzes bio-based chemicals, bio-based plastics and bio-based macromolecular materials (textiles and paper). Although bio-based building materials, furniture and so on have large output and huge carbon reduction benefits, owing to the relatively simple conversion process, their bio-based products' conversion technology will not be discussed.

1.3.1 Bioenergy

Biomass energy, as a renewable energy source, has advantages such as renewability, low-carbon emissions and abundant resource reserves, compared with non-renewable energy sources like coal, oil and natural gas. After coal, petroleum and natural gas, bioenergy is the fourth-largest energy source in the world (Saxena *et al*. 2009). The growing bioenergy industry not only helps address energy crises, protect the environment and promote rural economic development but also drives the development of related industries.

Bioenergy utilization refers to the conversion (or direct use) of biomass resources as energy sources, such as anaerobic fermentation and direct combustion for power generation. In terms of biomass energy products, research mainly focuses on solid biofuels (biomass briquettes, biomass direct power/heat generation), gas biofuels (biogas and methane for vehicles, biohydrogen), and liquid biofuels (fuel ethanol, biodiesel). The most mature and widely developed utilization methods for biomass energy globally include biomass direct combustion power generation (Overend 2009), bio-liquid fuels (Singh 2022), biogas (Scarlat 2018), and biomass briquettes (Ferronato 2022). Commercialized products mainly include biomass power generation/heat supply, biogas, methane for vehicles, fuel ethanol and its downstream products, and biodiesel. The EU has established a mature technical system and industrial model covering the entire industry chain from raw material collection, storage and preprocessing to fuel production, distribution and application. The technical systems of developed countries are also becoming increasingly perfect while developing countries still need to focus on technological breakthroughs in key areas (Yuan and Zhu 2018).

1.3.2 Bio-based chemicals

Bio-based chemicals refer to a category of chemicals produced using renewable biomass resources through physical, chemical, biological and other methods (Van Schoubroeck 2018). They offer advantages such as renewable feedstock, minimal environmental pollution and carbon emission reduction. In certain sectors, bio-based chemicals are gradually replacing traditional petroleum-based chemicals, serving as a new engine for advancing green and low-carbon economic development.

Depending on their properties, bio-based chemicals can be categorized as biodegradable, non-biodegradable, monomers, polymers, platform compounds and derivative compounds. For instance, ethanol is a biodegradable monomeric platform compound, polylactic acid is a biodegradable polymer derivative compound, and 2,5 Furandicarboxylic acid (FCDA) is a non-biodegradable monomeric platform compound. Platform compounds in particular can serve as chemical monomers for high-value polymer materials and other chemical products, such as acetylpropionic acid and 5-hydroxymethylfurfural (HMF). Through bio-based platform compounds, various high-value and more complex bio-based chemicals or materials can be derived, such as bioplastics and fibres. This represents a crucial pathway to replacing traditional petrochemical and coal chemical industries and transition towards green chemistry, offering vast prospects in future markets (Philp 2018).

Table 1.1 Bio-based platform chemicals classification

Classification	Bio-based platform chemicals
Acids	Lactic acid, Succinic acid, Levulinic acid, Hydroxypropionic acid/aldehyde
Alcohols	Ethanol, Glycerol and derivatives, Sorbitol, Xylitol
Furans	Furfural, HMF, FDCA
Biohydrocarbons	Isoprene

As early as 2004, the US Department of Energy proposed a list of 12 bio-based platform compounds with high added value that could be commercially produced on a large scale and converted to other chemicals and products (Werpy *et al*. 2004). In 2010, Bozell and Petersen updated this list based on technological developments, including ethanol, furans (furfural, HMF, FDCA), glycerol and derivatives, biohydrocarbons (e.g. isoprene), lactic acid, succinic acid, acetic acid, hydroxy propionic acid/aldehyde, sorbitol and xylitol (Bozell and Petersen 2010). These platform compounds can be categorized into four major classes: acids, alcohols, furans and olefins, as detailed in Table 1.1.

1.3.3 Bio-based plastics

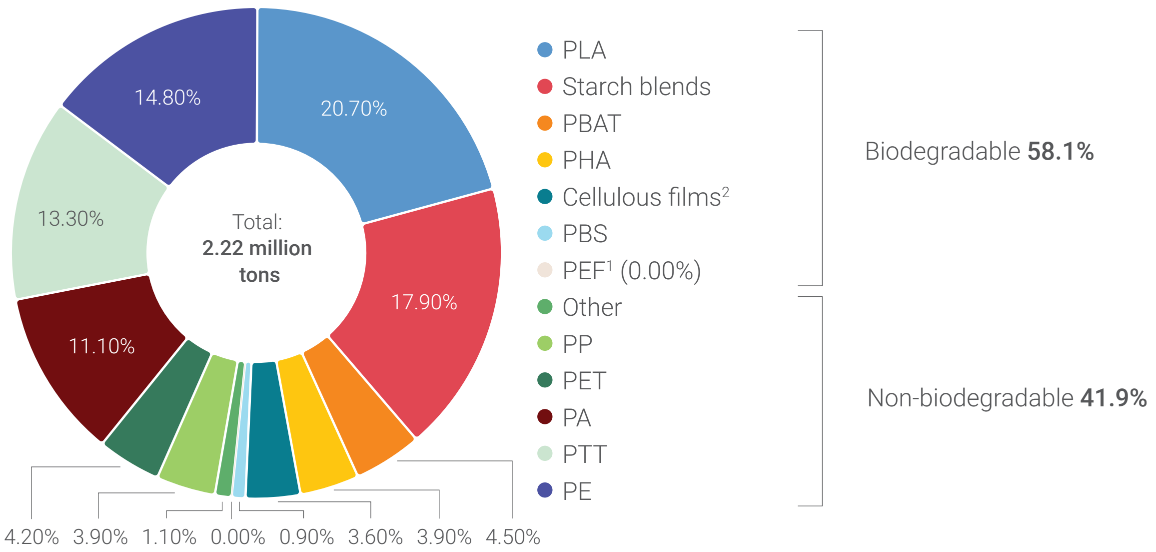
Bio-based plastics are plastics whose raw materials are partially or wholly derived from biomass. Bio-based plastics can be categorized into degradable and non-degradable according to whether they are biodegradable.

Microorganisms can degrade biodegradable bio-based plastics in specific environments and completely transform them into environmentally sound substances such as carbon dioxide (CO_2) and water (Gironi *et al*. 2011). This kind of material has the property of complete degradation in the environment after disposal, which can eliminate “white pollution” and protect the natural environment. Because of its biodegradability, the biodegradable bio-based plastics must keep dry and avoid light during storage and transportation. It has a wide range of applications, mainly including plastic packaging film, agricultural film, disposable plastic bags, disposable plastic tableware and so on.

Non-biodegradable bio-based plastics denote plastics that cannot be degraded by microorganisms in the environment (Ferreira-Filipe *et al*. 2021). The main target market for these materials is to supplement petroleum-based plastics and replace existing petroleum-based similar products to save petroleum resources and reduce carbon emissions. The main application areas are packaging, consumer goods, textiles, etc. (Altman 2023).

According to European Bioplastics Association (European Bioplastics) data, global bio-based plastics account for about 1 per cent of the annual production of plastics. Global bio-based plastics production capacity reached 2.22 million tons in 2022, of which 1.08 million tons were non-biodegradable products. The common products include bio-based polyethylene terephthalate (PET), polyethylene furanoate (PEF), polyamide (PA), polyethylene, polypropylene (PP), polytrimethylene terephthalate (PTT). The capacity of biodegradable plastics is 1.14 million tons, and common products include bio-based polylactic acid (PLA), polyhydroxyalkanoates (PHA), polybutylene succinate (PBS), polybutylene adipate terephthalate (PBAT), starch blends and cellulose films. These 12 types of products account for 99.9 per cent of the total output of bio-based plastics, as shown in Fig. 1.1.

Fig. 1.1 Global production capacities of bioplastics 2022



[1] PEF is currently in development and predicted to be available at commercial scale in 2023.

[2] Regenerated cellulose films.

1.3.4 Natural fibres for textile

Natural fibres are the fibres obtained directly from the original or artificially cultivated plants and artificially bred animals in nature, represented by cotton, flax, silk and wool, which are important sources of materials for the textile industry (Kozlowski and Mackiewicz-Talarczyk eds. 2020). Natural fibres were once essential textile fibre raw materials for human daily life; but this situation has changed dramatically following the emergence of chemical fibres. In the early twentieth century, with the development of chemical synthesis technology, there were many new artificial fibres and synthetic fibres, such as viscose fibre, polyamide and polyester. Compared with natural fibres, these chemical fibres have higher strength, heat resistance, corrosion resistance, and other advantages, but also have a lower cost and a more comprehensive range of applications. As a result, chemical fibres have formed an intense competition and substitution for natural fibres. In the mid-to-late twentieth century, chemical fibres occupied most of the global textile market, while natural fibres were gradually relegated to a secondary position (Nayak *et al*. 2023). In the twenty-first century, with the continuous development of the economy and society, people's living standards have increasingly improved, and the pursuit of environmental protection and health has also grown. People recognize the environmental pollution and potential health risks that the production process of chemical fibres may cause, and the demand for sustainable textiles continues to grow, while natural fibres are regaining favour with consumers because of their renewable and biodegradable characteristics (Kozlowski and Muzyczek 2023). This report focuses on three main types of natural fibres, cotton, silk and hemp, as a reflection of the role of natural fibres in the bio-based circular economy.

1.3.5 Pulp and paper products

Pulp and paper products are typical biomass-derived products that mainly use the cellulose component of wood and agricultural straw. The pulp and paper industry displays a high degree of diversity across various facets, including product range, source materials, quality variations, distribution channels and end applications. Cellulosic fibres and other botanical materials serve as the foundational elements for crafting pulp and paper, occasionally supplemented by synthetic materials to confer distinct characteristics on the final output.

While most paper production relies on wood fibres, alternative sources like rags, flax, cotton linters and bagasse (a residual by-product of sugar cane) find application in specific paper types (Sun, Wang and Shi

2018). Recycling is a key practice in the industry, with used paper undergoing purification and sometimes deinking before being amalgamated with fresh fibres and reconstituted into new paper. Additionally, wood pulp (cellulose) forms the basis for a range of other products, including diapers, rayon, cellulose acetate and cellulose esters, employed in creating textiles, packaging films and explosives. Pulps created through various methods possess distinct properties that make them suitable for particular products. Most pulp is generated to be further processed into paper or paperboard, but a portion of it is earmarked for alternative uses like robust fibreboard or textile items crafted from dissolved cellulose.

2

Global bioeconomy policy overview and emerging trends

2.1 Historical evolution of key bioeconomy policies

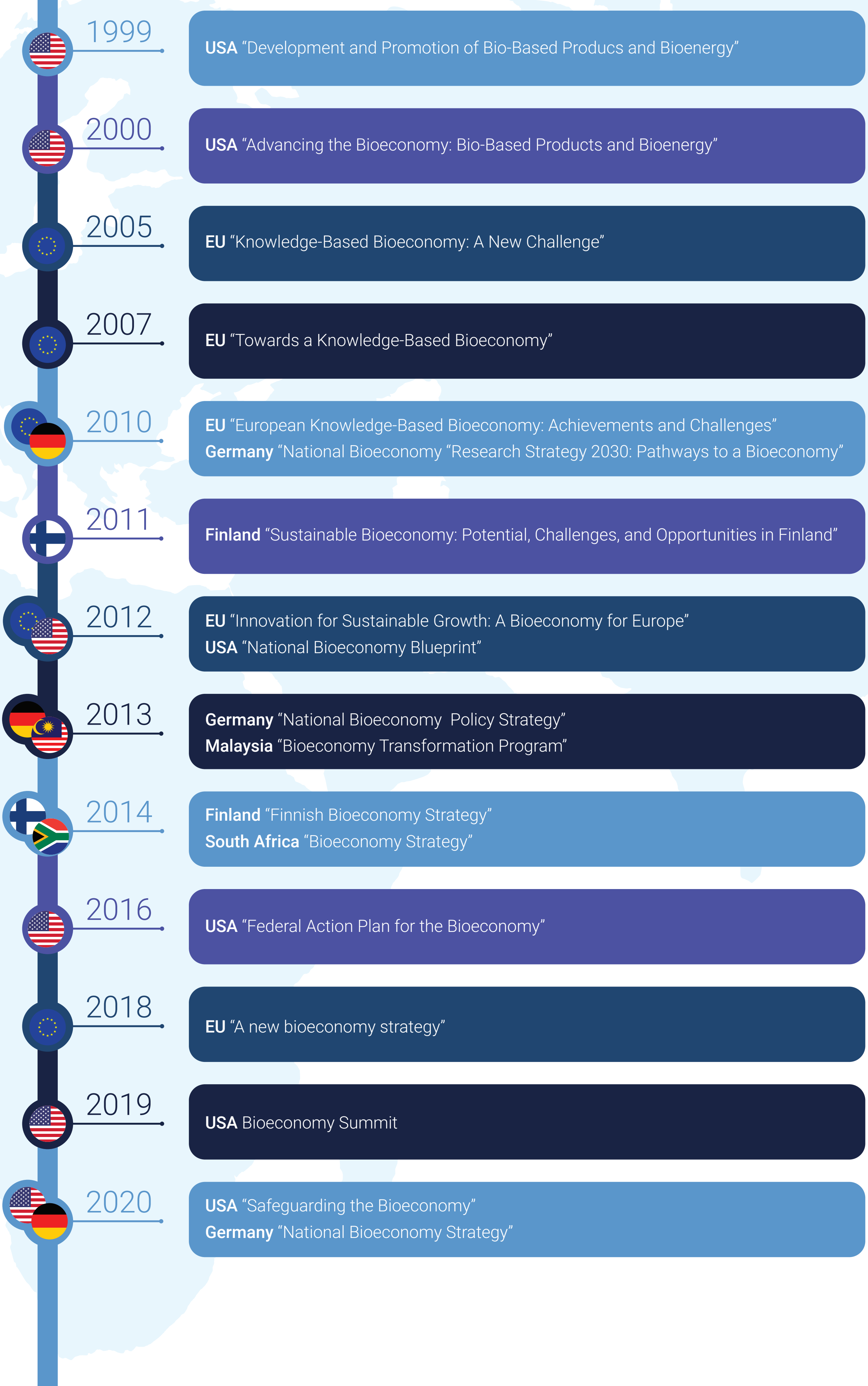
Bioeconomy strategies and policies began in 1999 with the USA issuing Executive Order 13134. This marked the formal introduction of the concept in August 1999. In 2000, the Biomass Research and Development Board, a federal inter-agency body, published a report titled “Advancing the Bioeconomy: Bio-Based Products and Bioenergy”. This report underscored the US Government’s recognition of biotechnology’s importance, offering policy recommendations to promote biotechnology for economic growth and sustainability.

Following closely, the EU implemented policies in subsequent years. In 2005, 2007 and 2010, the EU released reports titled “Knowledge-Based Bioeconomy: A New Challenge”, “Towards a Knowledge-Based Bio-Economy” and “European Knowledge-Based Bioeconomy: Achievements and Challenges”, respectively. These policy documents further emphasize the crucial role of knowledge in the bioeconomy. They propose measures such as establishing specialized investment platforms for the circular bioeconomy and developing sustainable biorefineries to drive the development of a new bioeconomy. This reflects the idea that, in the bioeconomy, knowledge and sustainability are key elements for achieving success. In 2010, Germany unveiled the “National Bioeconomy Research Strategy 2030: Pathways to a Bioeconomy”. Aimed at developing a sustainable bioeconomy that follows natural material cycles, the strategy ensures diverse diets and enhances national competitiveness through high-value renewable products. In 2011, Finland released the report “Sustainable Bioeconomy: Potential, Challenges, and Opportunities in Finland”, which highlights the potential of Finland’s bioeconomy and identifies challenges such as resource management, environmental sustainability and technological innovation. This helps other countries understand the potential issues they may encounter in bioeconomy development and provides strategies to address these challenges. In 2012, the EU released “Innovation for Sustainable Growth: A Bioeconomy for Europe”, positioning the bioeconomy as a key driver for implementing the Europe 2020 strategy, achieving smart and green growth and promoting the transition to economic forms that make greater use of renewable resources. During the same period, the US Government introduced the “National Bioeconomy Blueprint”, highlighting the bioeconomy as a critical factor in driving technology-driven economic growth in human health and medicine, bioenergy, agriculture, environmental protection and biomanufacturing. Technological innovation was emphasized as a significant driver of economic growth. In 2013, Germany published its “National Bioeconomy Policy Strategy”, aiming to promote food security, environmental protection and the utilization of renewable resources. This strategy sought economic and social transformation through bioeconomy development, reduced reliance on petroleum energy, created employment opportunities and enhanced Germany’s global competitiveness in economics and research (Germany, Federal Ministry of Food and Agriculture 2014). In 2014, Finland continued its efforts with the “Finnish Bioeconomy Strategy”, aimed at advancing technology in crucial areas like biotechnology and clean technology, creating new job opportunities and leading Finland toward a sustainable, low-carbon and resource-efficient society (Finland 2014).

In 2013, Malaysia also released its “Bioeconomy Transformation Programme”, signalling that those Asian developing nations had recognized the strategic importance of the bioeconomy. The bioeconomy encompasses various fields such as agriculture, biotechnology, forestry, fisheries, food production and biomedicine and is considered a future driver of economic growth. During the same period, South Africa introduced its “Bioeconomy Strategy”. Among developing nations, some countries with relatively abundant biological resources, such as Malaysia, South Africa, Thailand and others, have formulated national strategic policies for the bioeconomy. Additionally, more than 30 other countries have developed bioeconomy strategic policies focusing on specific sectors or industries. However, countries that have not yet formulated national, sectoral or departmental bioeconomy strategies are primarily in Eastern Europe, Western Asia, South Asia, Africa, and Central and South America.

In 2016, the USA published *The Billion Ton Bioeconomy Initiative: Challenges and Opportunities*, describing the policy actions taken by eight federal departments to promote the development of the bioeconomy (USA, Biomass Research and Development Board 2016). In 2018, the EU released a new bioeconomy strategy, outlining three key action plans and policy measures: strengthening bio-based industry development, establishing a dedicated investment platform for circular bioeconomy and promoting the development of new sustainable biorefineries. It also includes establishing an EU bioeconomy policy support mechanism within the "Horizon 2020" programme to drive regional and member States' policy development. Bioeconomy development pilot projects are also being conducted in rural, coastal and urban areas. The European Commission is implementing ecological and environmental policies, including establishing a monitoring and assessment system across the EU to track progress in sustainable and circular bioeconomy, utilizing platforms like the Knowledge Centre for Bioeconomy to collect and access relevant data and information, enhancing public awareness and understanding, and providing guidance and examples for operating the bioeconomy system within ecological safety limits (European Commission 2018a). In 2019, the US Office of Science and Technology Policy hosted the Summit on America's Bioeconomy, proposing the construction of a future bioeconomy workforce, promoting and protecting critical bioeconomy infrastructure and data, and strengthening the USA's innovation ecosystem to prioritize bioeconomy development in critical research and development budgets (USA, White House, Office of Science and Technology Policy 2019). In 2020, the US National Academies of Sciences, Engineering and Medicine (2020) published the report "Safeguarding the Bioeconomy", outlining the risks faced by the USA's bioeconomy and strategic measures to maintain its leadership position. During the same period, Germany released a new "National Bioeconomy Strategy", outlining guiding principles, strategic goals and priority areas for Germany's future bioeconomy development.

Fig. 2.1 Bioeconomy policy timeline



1999 **USA** “Development and Promotion of Bio-Based Producs and Bioenergy”

2000 **USA** “Advancing the Bioeconomy: Bio-Based Products and Bioenergy”

2005 **EU** “Knowledge-Based Bioeconomy: A New Challenge”

2007 **EU** “Towards a Knowledge-Based Bioeconomy”

2010 **EU** “European Knowledge-Based Bioeconomy: Achievements and Challenges”
Germany “National Bioeconomy “Research Strategy 2030: Pathways to a Bioeconomy”

2011 **Finland** “Sustainable Bioeconomy: Potential, Challenges, and Opportunities in Finland”

2012 **EU** “Innovation for Sustainable Growth: A Bioeconomy for Europe”
USA “National Bioeconomy Blueprint”

2013 **Germany** “National Bioeconomy Policy Strategy”
Malaysia “Bioeconomy Transformation Program”

2014 **Finland** “Finnish Bioeconomy Strategy”
South Africa “Bioeconomy Strategy”

2016 **USA** “Federal Action Plan for the Bioeconomy”

2018 **EU** “A new bioeconomy strategy”

2019 **USA** Bioeconomy Summit

2020 **USA** “Safeguarding the Bioeconomy”
Germany “National Bioeconomy Strategy”

2.2 Global bioeconomy policy frameworks

2.2.1 Europe

In Europe, the EU plays a key role in developing national bioeconomy policy strategies. One of the core objectives of the EU strategy is to adapt to a policy environment that has changed significantly, especially concerning the EU circular economy, the Paris Agreement and the 2030 Agenda for Sustainable Development. Germany was the first country to publish a dedicated national bioeconomy research strategy in 2010. In addition, the bioeconomy in European countries has often been implemented in the context of green or blue growth strategies with a focus on the circular economy over the last few years.

The EU

The cross-sectoral nature of the bioeconomy and its diversity within Europe is largely due to the rich multidimensional and multilevel policy landscape resulting from the EU's biophysical characteristics and industrial specialization. Thus, the European bioeconomy is shaped by policies with different approaches at different levels, including at the EU level, the dedicated European Bioeconomy Strategy, overarching policies such as the European Green Deal (EGD); cross-cutting policies and related programmes such as Research and Innovation, Regional Development, Climate Change, Environmental Protection, Circular Economy and Blue Economy; as well as sectoral programmatic policies focusing on specific bioeconomy sectors including biomass-producing sectors and those that primarily utilize biomass.

The EU Bioeconomy Strategy was first published in 2012, reviewed in 2017 and updated in 2018. The strategy aims to achieve five distinct objectives and thus provides a coherent framework that favours synergies and addresses trade-offs between sectors and objectives (European Commission 2012). In 2019, the European Commission launched EGD, which aims to transform the EU into a modern, resource-efficient and competitive economy with net-zero greenhouse gas (GHG) emissions by 2050 and decouple economic growth from resource use (Fetting 2020). To achieve these goals, EGD triggers a series of initiatives across the EU policy spectrum for 2020–2022. The latest Global Bioeconomy Policy Report (IV), released in 2020, mentioned that in recent years, the EU had been placing greater emphasis on leveraging advances in life sciences and biotechnology to modernize and strengthen traditional industries in Europe.

Germany

In 2010, Germany published a dedicated National Bioeconomy Research Strategy (Germany, Federal Ministry of Education and Research 2011) and a dedicated National Bioeconomy Policy Strategy three years later (Germany, Federal Ministry of Food and Agriculture 2014), making Germany one of the world leaders in bioeconomy policy. In 2017, the High-Tech Forum's recommendations on German innovation policy listed the bioeconomy as one of the six new themes for the future (Germany, Federal Ministry of Education and Research n.d.). The 2018 coalition agreement reaffirms that the bioeconomy can help drive the transition to a renewable resource-based economy (Germany 2018). It further emphasizes the cross-sectoral agenda "From Biology to Innovation" led by the Federal Ministry of Education and Research (BMBF) and the Federal Ministry of Economic Affairs and Energy, which has been developed in conjunction with industry, the scientific community and civil society to integrate biological knowledge, biotechnology and biomimetic processes more strongly into the realm of life and business (BMBF 2018). The German Government, following its presidency of the Council of the EU, published in July 2020 the Plan for the German Presidency of the Council of the EU in the fields of education and research and innovation, which identifies the bioeconomy as a key area of action and a critical area (BMBF 2020).

United Kingdom

As a country poor in biomass resources, the United Kingdom (UK) has sought to capitalize on its strengths in adding value to by-products and waste solid and build a strong knowledge base closely linked to industry. In 2011, the Natural Environment White Paper set out a sustainable agricultural vision over the next 50 years (UK, Department for Environment and Rural Affairs 2011). This will give rise to “green food” projects that will work towards the sustainable intensification of the agricultural and food supply chain. It saw the publication of the Anaerobic Digestion Strategy and Action Plan in 2020, which aims to help divert waste from landfills, reduce GHG emissions and produce renewable energy.

In 2012, a specific United Kingdom Bioenergy Strategy was adopted, envisaging the mandatory use of biomass to meet the its goal of decarbonization by 2050 and emphasizing the use of a wide range of waste materials and perennial energy crops (UK, Department of Energy and Climate Change 2012). In a 2015 parliamentary-driven policy report on “Building a high-value bioeconomy: opportunities from waste” (UK 2015), the UK Government sought to develop a national bioeconomy strategy and utilize biological remains and wastes as a resource for high-value products, thereby promoting a circular economy. After high hopes from academia and industry and more than two years of development, the United Kingdom launched its dedicated bioeconomy strategy in 2018, “Growing the Bioeconomy: Improving lives and strengthening our economy: A national bioeconomy strategy to 2030” (UK 2018), aiming to double the scale of the bioeconomy’s impact. Previous road maps and strategies were updated and bundled under the leadership of the Department for Business, Energy and Industrial Strategy (2017) to form an industrial strategy focused on leveraging world-class research and development and scaling up investment.

2.2.2 Asia-Pacific

Some of the Asia-Pacific region’s emerging economies have been rated as among the most innovative in the world, with bioeconomy development in Asia generally being more oriented towards high-tech and industrial innovation. Some countries (e.g. Japan and Thailand) have adopted specialized bioeconomy strategies, while others related to the bioeconomy reflect the region’s high-tech vision and focus on biotechnology (e.g. China, India and Republic of Korea). Innovation in the bioeconomy is considered particularly important for improving human health in the health-care sector, which works closely with the bio-industry. Large industrial economies such as China’s and India’s see biotechnology as an emerging area of innovation in which they can compete quickly.

China

China is a large agricultural country, rich in biomass resources. Bioeconomy has always been one of its industry’s key concerns, from its Tenth Five-Year Plan to the Fourteenth Five-Year Plan. During the Twelfth Five-Year Plan period, the Government of China put forward the strategic requirements of promoting the integration of urban and rural development and building an ecological civilization, clarified the tasks of promoting the revolution of energy production and consumption, and committed to the international community to achieving China’s non-fossil energy development goals in 2020 and 2030. The development of China’s biomass industry has encountered a good strategic opportunity.

The Twelfth Five-Year Plan for the development of national strategic emerging industries clearly puts forward the orderly development of biomass direct-fired power generation; actively promotes biomass gasification and power generation, biomass moulding fuels, biogas and other distributed biomass energy applications; strengthens the development of next-generation biofuel technology; and promotes the industrialization of cellulose-based ethanol and microalgae biodiesel. Since the Twelfth Five-Year Plan, China's biomass energy utilization technology diversification, biomass power generation, liquid fuels, gas, moulded fuels and other technologies continue to progress. The formulation of the Fourteenth Five-Year Plan for National Economic and Social Development and the Visionary Goals for 2035 explicitly propose promoting clean, low-carbon, safe and efficient energy utilization. The Fourteenth Five-Year Plan for the Development of Renewable Energy, issued in 2022, and the "three-year action plan to accelerate the innovative development of non-food bio-based materials", issued in 2023, both aim to promote bioenergy use and bio-based product development (China, Ministry of Industry and Information Technology *et al*. 2023). The "Accelerate the development of plastic to bamboo" Three-Year Action Plan highlights the multiple usability of bamboo materials to substitute petroleum-based plastics (China, National Development and Reform Commission *et al*. 2023).

Japan

Japan has a long history of promoting biomass production and industrial utilization. The "Biomass Japan Strategy" was first created in 2002 to build a sustainable economy by efficiently using biological resources. It was revised in 2006 to emphasize bioenergy and "biomass towns", eco-friendly and disaster-resistant communities using integrated biomass.

In terms of biotechnology promotion, Japan launched the Biotechnology Strategy Committee in 2002, chaired by its Prime Minister, as well as a comprehensive set of biotechnology strategy guidelines containing 200 detailed action plans for developing the Japanese biotechnology industry (Japan, Prime Minister of Japan and His Cabinet n.d.). The Japanese Government then established the Government-Industry Biotechnology Strategy Promotion Committee in 2008 and issued a new strategy, "Dream BT Japan" (Japan 2008). In 2010, the National Biomass Utilization Promotion Plan set quantitative utilization targets (e.g. fixed quotas for biofuels) for 2020 at the national, local and district levels. The plan considers the entire value-added chain from residue recovery to biorefining. In June 2019, Japan adopted its first dedicated bioeconomy strategy, based on the Bio Strategy Working Group report, and updated it in June 2020 (Japan 2018). With a strong bio-industry and research background, the strategy focuses on the high-tech aspects of the bioeconomy.

2.2.3 Americas

In recent years, the bioeconomy concept has gained significant political importance in Latin America and the Caribbean. The Latin America and Caribbean region has also made important progress in areas such as bioenergy, agricultural biotechnology, low-carbon agriculture, biodiversity use and ecosystem services. Countries such as Argentina, Brazil and Colombia have been working for years to develop dedicated strategies, but progress has been slow. In August 2020, Costa Rica became the first and only country to publish a dedicated national strategy in Latin America.

In North America, the USA is at the forefront with a comprehensive, dedicated bioeconomy strategy that uniquely emphasizes the role of biotechnology, the importance of biomedicine and its application to national defence . Since then, a more agricultural and bioresource-based vision has evolved, driven by various federal agencies. On the other hand, Canada has taken a different path in developing its bioeconomy in the form of an industry-driven national strategy focusing primarily on access to agricultural biomass.

Costa Rica

Costa Rica is at the forefront of sustainable development. In the 1980s, further policies were introduced to open up trade and diversify production. Internationally recognized measures have been taken in areas related to the bioeconomy, such as biodiversity, forestry, climate change, sustainable agriculture, clean energy and sustainable tourism.

For instance, in 2008, the Costa Rican Government approved the National Biofuels Plan to gradually replace fossil fuels with renewable energy sources (Costa Rica, Ministry of the Environment and Energy, Ministry of Agriculture and Livestock 2008), aiming to enhance social development and contribute to GHG reduction. In 2020, the Government unveiled the National Bioeconomy Strategy, Costa Rica 2020–2030, during a launch event attended by the President (Costa Rica 2020). This made Costa Rica the first country in Latin America and the Caribbean to adopt a dedicated national bioeconomy strategy. The bioeconomy represents an opportunity for Costa Rica to integrate production development policies and environmental policies established over the past seven decades. It aims to harmonize the goals of production development with the conservation, knowledge and sustainable utilization of national biological wealth.

United States

In 2012, the White House released a dedicated US bioeconomy strategy, the “National Bioeconomy Blueprint” (USA, White House 2012), covering the entire bioeconomy portfolio with an emphasis on biotechnology and biomedicine. With the release of its strategy, the USA became the first country to describe biotechnology as a key driver of the bioeconomy. The agricultural strategies and updates to the Agricultural Act, formulated by the US Department of Agriculture from 2014 to 2018, did not specifically address the bioeconomy but played a crucial role in advancing key subsectors in agriculture, bioenergy and food. These initiatives expanded efforts related to bio-based product procurement (BioPreferred Program) and biorefining assistance programmes (renamed the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program), as well as biomass crop assistance programmes (USA, Department of Agriculture n.d.). Additionally, the BioPreferred Program, through federal procurement initiatives and voluntary certification and labelling programmes, has become a significant supporter of the US bioeconomy. Since the voluntary certification programme’s launch in 2011, over 3,000 bio-based products have received certification and labelling (National Academies of Sciences, Engineering and Medicine 2020).

The USA is leading in many biotechnology fields and has been actively modernizing its regulatory framework in recent years. In 2017, the Department of Agriculture issued a report from an inter-agency working group outlining the need to enhance public acceptance, modernize and simplify federal regulation of biotechnology products and accelerate the commercialization of biotechnology products. The White House also released an “Update to the Coordinated Framework for the Regulation of Biotechnology”, aimed at streamlining regulatory processes and expediting the market entry of biotech innovations. In 2022, the White House launched a National Biotechnology and Biomanufacturing initiative to accelerate biotechnology innovation and grow the US bioeconomy across multiple sectors, including health, agriculture and energy.

Canada

Canada holds some of the wealthiest and most sustainable biomass resources in the world, and this wealth of natural resources has shaped the country’s entire coast. Historically, Canada’s traditional industries (forestry, agriculture, fishing, mining, etc.) have been the primary economic drivers that have created the fabric of Canadian commerce and culture. Science and technology are playing an increasingly important role in maximizing the value and economic contribution of Canada’s natural resources. By combining technological advances with Canada’s traditional economic sectors, we can see the foundation of Canada’s industrial bioeconomy.

As the landscape of Canadian agriculture continues to change in the twenty-first century, new policies need to reflect flexible responses to these changes. For example, the signing of the Paris Agreement in

2015 and the Vancouver Declaration on Clean Growth and Climate Change at the national level in early 2016 attest to Canada's growing need for sustainable agriculture and climate change mitigation. Trends in Canada's sustainable agriculture and agrifood systems also provide opportunities to strengthen and diversify the industry by converting agricultural outputs, residues and wastes into high-value bioproducts, developing new and stress-tolerant crops and improving long-term environmental sustainability

2.2.4 Africa

Bioeconomy initiatives in Africa are growing rapidly. The continent is recognized as one of the regions with the greatest potential for bio-based economic development because of its rich biomass resources. South Africa released a dedicated bioeconomy strategy in 2013 and the "Southern Africa Regional Strategy 2020–2024" in 2020, the first dedicated bioeconomy strategy on the continent. Seven East African countries, supported by the East African Innovation Network for the Development of Bioresources, have come together to develop aregional innovation-driven bioeconomy strategy to facilitate technology transfer and business development.

South Africa

South Africa stands out with a dedicated bioeconomy strategy among all African countries. In 2013, the Government released the "South African Bioeconomy Strategy" (South Africa, Department of Science and Technology 2013) to facilitate the transition to a knowledge-based bioeconomy. As a country with one of the highest levels of biodiversity in the world, South Africa is endowed with abundant natural resources, giving the South African Government an early focus on biodiversity and uniquely integrating health and medical aspects into its strategy. Building on the experience of two previous initiatives, the National Biotechnology Strategy (2001) (South Africa 2001) and the Ten-Year Innovation Plan (2008), the Government issued a bioeconomy strategy aimed at guiding investment in bioscience research and innovation as well as policymaking.

South Africa's vision is that, by 2030, the South African bioeconomy will significantly contribute to the country's economy in terms of GDP. In addition, the South African Government is actively engaged in international cooperation, in partnership with the Departments of Science, Technology and Innovation in Botswana, Namibia, Tanzania and Zambia, as well as the secretariat of the Southern African Development Community.

2.3 Emerging trends in global bioeconomy policies

The economic policies about bio-based products have made significant strides, ensuring that global SDGs could be realized. We will delve further into emerging trends in global bio-based economy policies, encompassing four pivotal dimensions that will play a crucial role in shaping the future of the bio-based products sector: life cycle carbon disclosure policies, trade policies, digital transformation policies, and carbon pricing policies and carbon credit policies.

2.3.1 Disclosure of the life cycle emissions of products

Before specific energy resources, chemicals and other products derived from biomass enter the market, a life cycle cost, resource utilization and environmental impact assessment should be conducted (Cascione *et al*. 2022). The assessment results should be compared with the life cycle analysis of traditional energy and chemical production processes to evaluate their respective costs and benefits. The life cycle stages should extend from resource production to transportation, processing, conversion, end-use and waste disposal/recycling. This will provide a balanced and meaningful comparison of bio-based and similar processes regarding internal and external costs and benefits. The life cycle analysis results should be used to identify where cost reduction and negative environmental impacts can be minimized and then to monitor these areas to find cost reduction methods.

Further, biomass-based technologies' life cycle cost and benefits should form a component of public education. When conducting economic and life cycle assessments, consideration should be given to GHG emission offsets. In recent years, disclosing carbon labels for bio-based products has become a new trend (Liu, Wang and Su 2016). A carbon label informs consumers in the form of a label about the CO_2 and other GHG emissions released during the production process. To some extent, a carbon label serves as a "green passport" for products. From the perspective of a green supply chain, publicly disclosing the carbon footprint of finished products in the form of carbon labels will make more companies pay attention to the carbon emission information of products when making purchases. They will prefer collaborators with carbon reduction awareness, thereby reducing the carbon emissions of the entire value chain of products.

For consumers, carbon labelling is a guide for daily consumption and the first threshold for consumers to understand carbon neutrality. Consumer low-carbon purchasing behaviour will further drive corporate decarbonization actions. For businesses, carbon labelling is a scientific quantitative tool and an important means to explore emission reduction potential.

2.3.2 Trade policy focusing on environmental, ecological, health and climatic impacts

An increasing number of countries and international organizations consider biodiversity conservation as a crucial objective. Policymakers are taking measures to ensure that trade does not threaten biodiversity while promoting sustainable utilization (Ji *et al*. 2020). To prevent illegal logging and wildlife trafficking, more and more countries are requiring importers to provide information on the origin and compliance of products. This helps ensure that products are obtained through legal channels while reducing the likelihood of illegal trade. The advancement of biotechnology has expanded the use of biological resources in producing medicines, chemicals and other products. International cooperation policies typically encourage sustainable utilization and sharing benefits from biological resources while ensuring their fair and equitable distribution. Emerging biosecurity issues such as bioterrorism and disease outbreaks drive international communities to enhance cooperation. International policymakers strive to implement measures to prevent the misuse or abuse of biological resources, thereby maintaining global security.

An increasing number of international companies and government agencies are focusing on sustainable supply chains and eco-friendly products. These policies encourage adopting sustainable production and procurement practices to reduce the consumption of biological resources and environmental impacts. New trends in bio-based trade and international cooperation policies primarily revolve around ecological conservation, health and human well-being, sustainable development, biological resource management and international security. Countries should leverage their comparative advantages in the vast potential market, actively establish strategic alliances with large multinational corporations in accordance with international conventions, establish joint ventures for domestic cooperation, collaborate in developing new products and jointly explore international markets. Further, it is crucial to encourage and support research institutions, especially enterprises, in establishing international collaborative networks to facilitate better communication and sharing advanced technologies and management experiences. Policymakers must pay more attention to carbon leakage, pollution transfer and ecological displacement caused by trade (Das and Gundimeda 2022).

2.3.3 Policy safeguards for digitalization

The significant advancements in the Internet have given rise to the digital economy, transforming our modes of operation and daily lives. Consequently, this progress has engendered a digital economy and shifted the traditional bioeconomy into a platform economy. This transformation is intricately linked not only to natural resources and technology but also to the complex trajectories of society, businesses and individuals. Driven by digital solutions, the bioeconomy has made substantial strides in recent years, aiming to achieve the long-term goal of transitioning from a traditional fossil-based economy to a bio-circular economy (Eastwood *et al*. 2023). Consumer preferences have increasingly leaned towards super-functionality, surpassing basic economic values and encompassing social, cultural and emotional values. In this context, the circular economy ultimately seeks to decouple global economic development from infinite resource consumption. Hence, the convergence of the digital and the bioeconomic, resulting in the emergence of a digital bioeconomy, caters to downstream shifts in consumer preferences. As well, these preferences lead to upstream linkages in the value chain. Therefore, the coupled evolution of the bioeconomy with digitalization and the upstream-downstream synergy constitutes the transformation of the bioeconomy into a digital platform industry.

This co-evolution-driven restructuring enables it to integrate new functionalities and transition towards new development trajectories aligned with the circular economy. This transformation corresponds to long-term shifts in societal preferences, leading to a resurgence in emerging economies. Their planned obsolescence management strategies also make this metabolic shift possible. Therefore, the planned elimination-driven circular economy trajectory achieved through coupling the bioeconomy with digitalization and co-evolution in upstream-downstream operations can be regarded as a structural source of the digital economy's revival.

2.3.4 Carbon pricing and carbon credit policies

The carbon pricing policy, primarily based on carbon trading mechanisms and taxation systems, constitutes a significant economic instrument for achieving GHG emission control objectives. It promises to become a cornerstone for cost advantages in the bio-based industry (Memari *et al*. 2018). Carbon trading policies mandate cost increases in the production and utilization of fossil fuels and products through market mechanisms and legal regulations, thereby creating cost advantages for bio-based products and guiding industrial transformation. Governments impose GHG emission caps through policy regulations on petrochemical companies. Companies exceeding these caps must purchase emission allowances from the carbon trading market. The higher the carbon price in the trading region, the larger the emission cap deficit and, consequently, the higher the production costs. In contrast, biomanufacturing companies exhibit lower emissions while contributing to GHG reduction. They can offset their production emissions by exchanging carbon credits and selling them in the market, translating this into a cost advantage. With higher production capacity and greater GHG reductions, economies of scale reduce costs, resulting in a competitive advantage.

Carbon credits, which are traded in the carbon credit market, are reductions in carbon emissions through voluntarily implemented mitigation activities. Buying carbon credits is a way for companies to address emissions they cannot eliminate. Many countries are combining local carbon credit mechanisms with carbon emissions trading systems or carbon taxes as offsets, which will be an important source of demand for carbon credits in the future. The bio-based product itself could be used as potential carbon credits.

The imposition of carbon taxes similarly signifies increased production costs for fossil-based products, which benefits the bio-based industry. In terms of the form of carbon taxation, some countries introduce it as an independent tax category, while others incorporate it into existing energy or consumption tax structures. In some cases, it replaces previous fuel taxes. Carbon taxes are typically levied on fossil fuels. Some EU countries enforce strict measures, such as Germany's imposing a consumption tax of 47.04 cents per litre on diesel, while the biodiesel tax, after tax reductions, is only 18.60 euro cents per litre.

2.4 Two examples of the impact of bioeconomy policies on livelihoods

The bioeconomy, a new economic paradigm, spans the agriculture, food, health care, energy and industrial sectors. National bioeconomy policies can significantly impact human livelihoods and transform lifestyles. In most cases, biotechnology and bio-industry development foster economic growth, employment and poverty reduction. Some bio-based projects support ecosystem services and biodiversity conservation. However, immoderate bioeconomy expansion can harm local livelihoods.

This subsection discusses local bioeconomy policies' benefits and risks, elucidating their mechanisms. It aims to inform future policy development and improvement for human livelihoods.

2.4.1 Palm oil: the gold oil that maintains Indonesia's trade balance

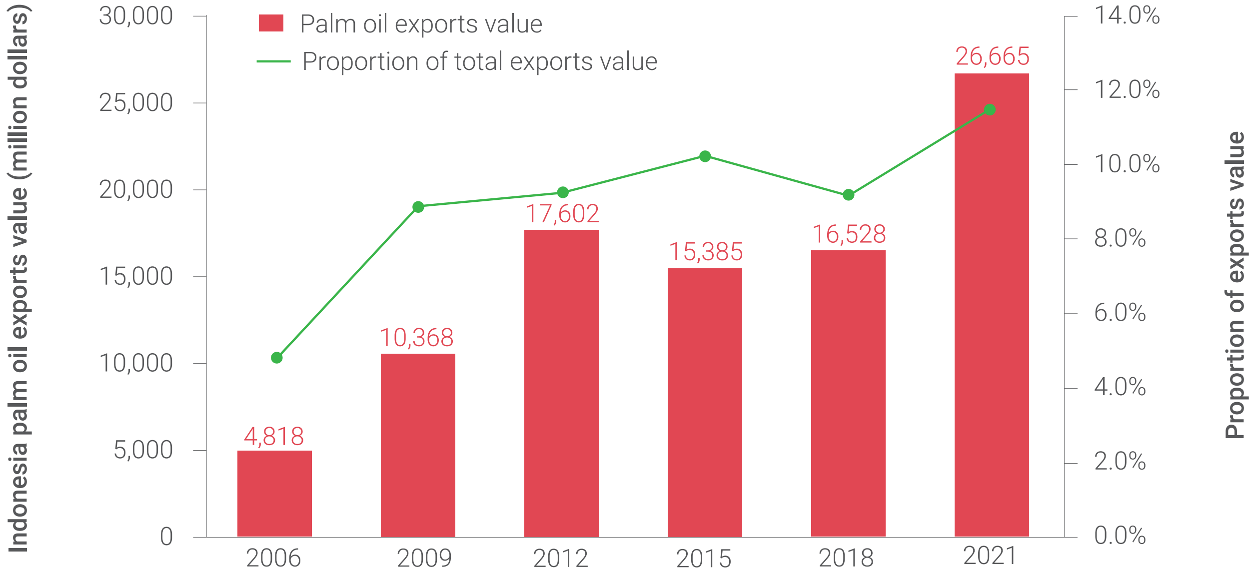
According to the Food and Agriculture Organization of the United Nations (FAO), global biodiesel production more than doubled between 2010 and 2020, reflecting a worldwide shift in energy consumption from fossil oil to biodiesel. Countries including Brazil, Colombia, France, Indonesia, Malaysia and the USA actively pursue biodiesel blending policies with higher targets. This has driven an expansion of oil palm cultivation in South-East Asia, primarily Indonesia and Malaysia.

Indonesia, a leading palm oil producer, possesses significant palm oil resources for biodiesel production. In response to fossil energy depletion and climate change, the Indonesian Government focuses on diversification to enhance national energy security, particularly by increasing renewable energy use. In 2006, Indonesia issued several key policies, including Presidential Instruction No.1/2006, to promote biofuel development. These measures significantly boosted domestic palm oil and palm biodiesel production.

The EU's 2020 Renewable Energy Directive mandates higher renewable energy use in the transport sector, driving European demand for biodiesel. Europe imports substantial quantities of low-cost raw materials like palm oil from countries such as Indonesia because of insufficient local vegetable oil resources. As the world's largest palm oil exporter, Indonesia benefits economically from palm oil exports. Biodiesel's rise stimulates the palm oil industry and creates employment opportunities for Indonesians.

Promoting economic development: Palm oil, as Indonesia's second-largest export product, contributes significantly to Indonesia's GDP. Relying on Indonesia's implementation of the B30 programme (biodiesel 30 per cent blend) greatly reduced the dependence on imported fossil fuels, which is significant for Indonesia to maintain the country's trade balance and current account deficit.

Fig. 2.2 Indonesia's palm oil exports value and its proportion of total exports value



Note: Data adapted from United Nations Comtrade (2023) using HS principles, including Total modes of transport and Total customs procedure codes.

Generating employment opportunities: The palm oil industry chain expansion enhances sectors such as edible oil, soap and cosmetics, contributing to rural poverty reduction. Such has been the case in Indonesia, with its poverty alleviation goals in rural areas being reduced, including for migrant workers and all household categories (FAO 2021). And the proportion of employment in rural areas is very high. In Riau Province, the direct employment ratio of the industry is about 17 per cent. In Siak County, the ratio is about 38 per cent (Ngadi 2013). It also substantially contributes to state revenues, with the Palm Oil Plantation Fund Management Agency generating USD 105 million in 2020 (Nurfatriani *et al*. 2018).

Supporting quality education: Palm oil cultivation increases the income level of households, enabling them to increase their consumption expenditure, especially on non-food and education (Euler *et al*. 2017). As a result, the dropout rate of palm oil families is relatively lower. Also, as fewer units of labour are required in the cultivation of palm oil compared with other crops (Chrisendo, Siregar and Qaim 2021), more children are freed from labour on family farms to pursue schooling instead.

Overall, the development of the bioeconomy in Indonesia is seen as an important means of achieving medium- and long-term development goals, focusing on the use of biomass resources such as palm oil to increase energy diversification and self-sufficiency (SDG 7) as well as promoting the modernization of agriculture and the transformation and upgrading of industry (SDGs 2, 9 and 12). The palm oil and biodiesel industry chain are central to supporting lives and livelihoods in Indonesia, especially in rebuilding the rural economy after major disasters such as epidemics.

2.4.2 Soybeans: driving domestic demand growth and ecological conservation in Brazil

Soybean is another important crop in the bioeconomy era. According to the Global Agricultural Supply and Demand Report released by the US Department of Agriculture, the world's soybean production in 2021/2022 was 385.52 million tons, primarily supplied by Brazil, the USA and Argentina. Approximately 94 per cent of global soybeans are dedicated to industrial processing, with 18–20 per cent used for edible oil, biodiesel and chemicals (Karp *et al*. 2022). The FAO Statistical Yearbook notes that 130 million hectares were planted with soybeans in 2021/2022, with Brazil cultivating 36.95 million hectares at an average yield of 3.38 tons per hectare and the USA planting 30.33 million hectares with an average yield of 3.19 tons per hectare (Embrapa 2020).

Promoting rural development: Soybean's agricultural production demands the application of modern technologies. Consequently, the majority of its production occurs in large estates equipped with substantial machinery, primarily situated in the central-west region in Brazil. In order to stimulate the development of the least developed regions characterized by small-scale production, managerial deficiencies and technological limitations in this country, the *National Plan for Biodiesel* was introduced in 2004. According to the programme, measures were taken to enhance the efficiency of smallholders, including creating provincial and municipal biofuel firms, providing technical support to cooperatives, and promoting intercropping. From 2008 to 2010, smallholder participation increased fourfold, exceeding 100,000 (Zapata, Vazquez-Brust and Plaza-Úbeda 2010). This had empowered small-scale producers with more employment opportunities and income (Schaffel *et al*. 2012; Bergmann *et al*. 2013; da Silva César *et al*. 2015; De Oliveira and Coelho 2017).

Maintaining food security: Since 2016, Brazil's soybean and biodiesel industry has shifted to larger, more efficient farms and businesses, growing to 27 per cent of the agricultural GDP and 7 per cent of the overall economy. Advanced breeding and transgenic technologies have improved soybean resilience and oil content, addressing food security and global edible oil and feed demands. Double-cropping of soybean and maize has also saved arable land, reducing land pressure in other pan-tropical countries experiencing rising food demand (Xu *et al*. 2021).

Maintaining energy security: Soybean biodiesel development reduces Brazil's dependence on fossil fuels, enhancing energy supply diversity. Modern agricultural methods, such as precision farming and mechanized harvesting, boost production efficiency and reduce energy waste. Soybean cultivation by-products, such as soybean straw, support biomass energy production, in turn advancing renewable energy use.

In contrast to Indonesia, Brazil's economic growth hinges on domestic demand, with foreign trade making up a smaller GDP share. Brazil's biodiesel policy prioritizes domestic market needs social welfare and regional development. The "Bioeconomy in Brazil" strategy aims to boost rural employment and income (SDGs 1, 2 and 8), leveraging biodiversity and biological resources to innovate products and services, enhance energy security and cut GHG emissions (SDGs 7 and 13).

2.4.3 Women's empowerment

The bioeconomy vision not only impacts technology and productivity but also fosters social change and reduces economic disparities. It significantly enhances gender equality by providing opportunities for underrepresented groups including women and minorities in STEM fields, as well as challenging stereotypes and career barriers. Bioeconomy projects, often linked to community and rural development, empower women in decision-making and project planning, elevating their social status and confidence. By offering economic participation for women, the bioeconomy fosters their financial independence, reducing household dependence and enhancing their role in decision-making and resource allocation.

Women also face challenges in accessing resources such as land, credit and technology (United Nations Environment Programme *et al*. 2013). In bioeconomy, where agriculture and natural resource management are important, addressing gender disparities in access to resources is essential to promoting equitable participation and benefits (FAO 2022).

2.4.4 Conclusions and prospects

Bioeconomy policies aim to drive biomass innovation, recycling and the coordinated development of bio-based industries. The sustainable bioeconomy's status and national strategies differ across countries, shaped by their unique circumstances. In Argentina, the bioeconomy focuses on sustainable development, particularly climate change mitigation (SDG 13) and poverty reduction (SDG 1) (Bracco *et al*. 2018). Germany prioritizes food security (SDG 3), transitioning to a renewable-based economy, biodiversity preservation and innovation (SDGs 6, 7 and 9). Malaysia sees the bioeconomy as a key driver of economic growth, emphasizing agricultural productivity, health-care innovation and sustainable industrial processes (SDGs 3, 9 and 15).

However, some potential threats still cannot be ignored. Questions about its increasing expansion have resurfaced along with the overall rise of the bioeconomy agenda. Experience has shown that environmental impacts, such as air and water pollution, are not the only problems but that political, economic and social issues cannot be ignored.

Food and fuel competition: Economic expansion can allow agricultural land to grow, with projected crop yields increasing by 1.4 per cent annually by 2030. However, diverting food crops or arable land for biofuel production may cause food scarcity, price hikes and increased hunger and malnutrition among people experiencing poverty. For instance, transforming grasslands or natural areas into oil palm plantations disrupts local livelihoods (Santika *et al*. 2019).

Human rights undermining: Palm oil cultivation and processing often entail significant land, water and labour requirements, resulting in social issues. Some countries and companies use forced land expropriation, deforestation and eviction of local residents to expand palm oil cultivation, violating the rights of Indigenous and Afro-descendant communities (Rulli *et al*. 2019). Inadequate regulation and standards in the palm oil industry have led to labour exploitation, environmental pollution and tax evasion, negatively impacting the industry (Tang and Al Qahtani 2020).

Equity concerns: Developed regions like Europe, with strong GHG reduction needs, may drive biofuel crop growth in Asia, Africa and Latin America, potentially straining land and resources in those regions while enhancing their economies. For example, the global palm oil market is dominated by Indonesia and Malaysia, generating substantial economic benefits.

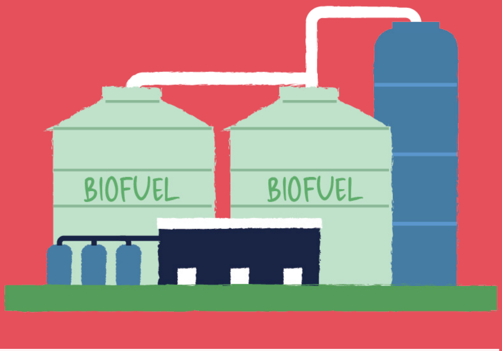
In contrast, some African countries face challenges with participating in the palm oil trade because of a lack of technical, financial and policy support, leading to imbalances in development and wealth disparities (Jha and Schmidt 2021).

Deforestation: Rising bioeconomy interest increases demand for wood biomass, potentially resulting in intensive forest management, monoculture planting, chemical use and forest clearing. Tropical countries face sustainability challenges, experiencing a net loss of approximately 7.6 million hectares of forest annually from 2010 to 2015 (FAO 2011a).

Biodiversity: The impacts of the bioeconomy on biodiversity are complicated. On the one hand, the bioeconomy can incentivize biodiversity conservation and restoration. Replacing fossil fuels with renewable bioresources reduces GHG emissions, mitigating climate change's threat to biodiversity. Utilizing high-value native and indigenous species enhances local community incomes, promotes biodiversity awareness and action and improves biodiversity monitoring with biotechnology and digital technologies. On the other hand, the bioeconomy can negatively impact biodiversity. Meeting biomass demand may overexploit land, water and natural resources, resulting in ecosystem degradation, pollution and destruction. Enhanced crop or animal yields may standardize genetic resources, reducing diversity. Using novel biological resources or technologies may introduce invasive species or genetically modified components that disrupt natural balances and evolutionary processes. Balancing these aspects is vital when formulating policies for a sustainable environment.

In summary, the bioeconomy offers economic growth, social welfare and environmental benefits but poses risks regarding food security, public health, social justice, cultural diversity and biodiversity. These effects are often unevenly distributed, requiring policy trade-offs for environmental sustainability.

3 Conversion technologies and prospects of bio-based products



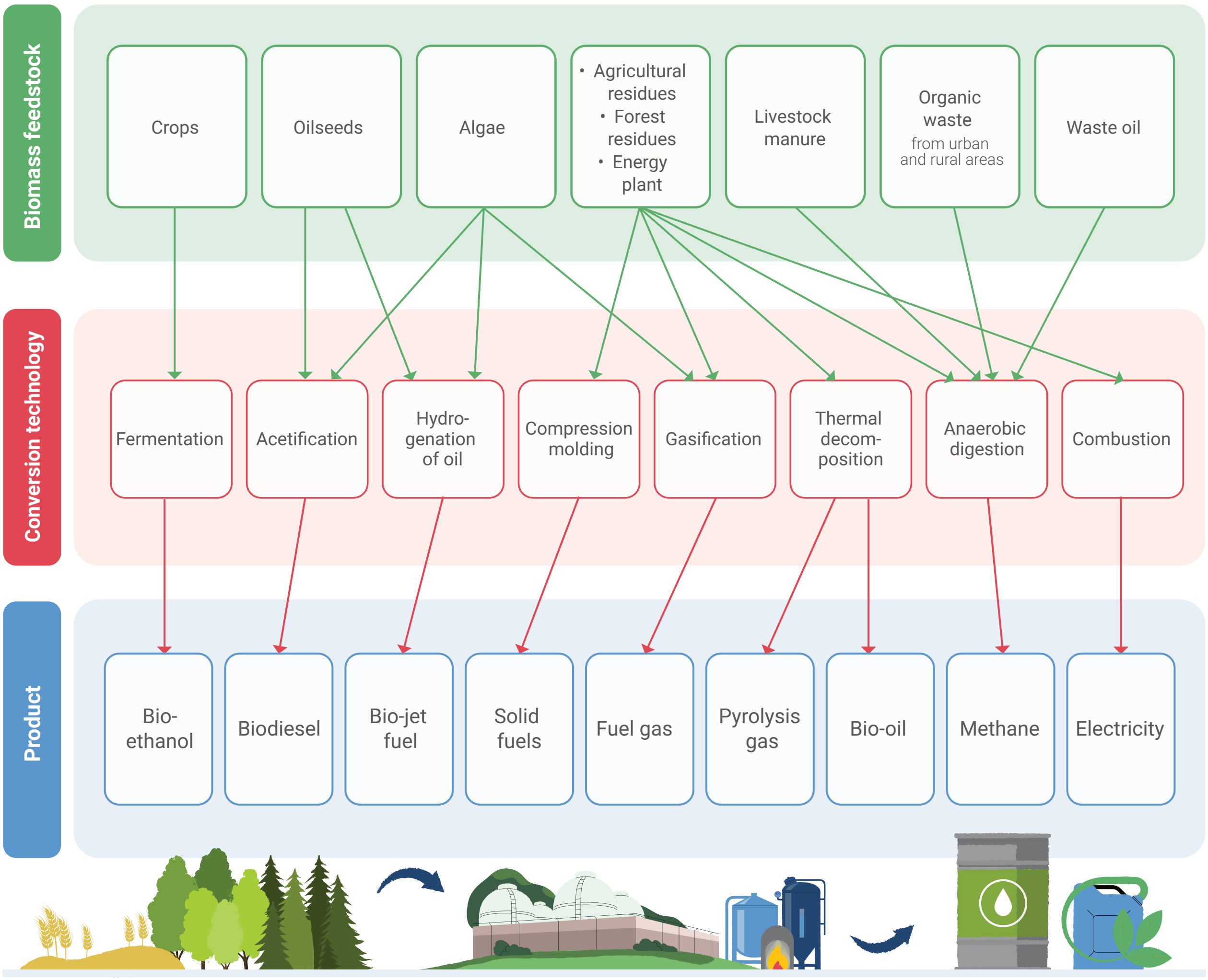
With the continuous introduction of bio-based products, bio-based products' production and conversion technologies is constantly innovative. This chapter analyzes the typical conversion technology of bio-based products (bio-based energy, bio-based chemicals, bio-based plastics, textiles and pulp products) and their development prospects.

3.1 Biomass energy products

3.1.1 Biomass energy products conversion routes

Based on physical properties, biomass energy can be divided into solid fuels, liquid fuels and other fuels. The main biomass feedstocks, conversion technologies and products are shown in Fig. 3.1. Solid fuel technologies mainly include biomass briquette technology and biochar technology. Biochar refers to a highly aromatic and non-melting carbon-rich substance produced from biomass through high-temperature decomposition under complete or partial anaerobic conditions (Pelaez-Samaniego *et al*. 2022).

Fig. 3.1 Pathways for the energy utilization of different biomass resources



Solid fuel technologies in Europe and the USA are at the forefront, with well-established standards systems. Germany, Sweden and other countries have solid fuel production capacities exceeding 20 million tons per year. China has made significant progress in producing and applying biomass solid fuels. However, in recent years, the development of the shaped fuel industry in China has shown a trend of initial growth followed by a decline. This has mainly resulted from the controversial environmental benefits of direct biomass combustion for power generation; and some provinces have even restricted biomass co-firing power generation projects (Ma *et al*. 2019).

Liquid biofuels, including fuel ethanol, biodiesel and bio-jet fuel, are the main biofuels, having an average compound annual growth rate of 4.1 per cent. According to current EU regulations, biofuels are divided into two categories. The first category is conventional biofuels, mainly produced from food crops such as rapeseed methyl ester, soy methyl ester and palm methyl ester. Conventional biofuels are still the primary type of biodiesel production. The second category is advanced biofuels, which are produced from non-food crops. There are two types in this category, namely PART A and PART B. PART A mainly uses non-edible parts of various crops as raw materials, producing bioethanol and hydrogenated vegetable oil. PART B mainly utilizes waste oils and fats, including animal fats, to produce used cooking oil methyl ester (Renewable Energy Directive and Renewable Energy Directive II). Currently, global bioethanol production mostly comes from starch biomass, while cellulosic raw materials have advantages since they do not directly compete with food. Compared with crops, cellulosic raw materials require less inputs (such as water, nutrients and land). However, due to immature technologies, the production cost remains high and is not suitable for large-scale industrial production.

Biogas technology has reached maturity and achieved industrialization. The biomass gasification process generates CO_2, carbon and high-calorific value gases such as hydrogen, methane, and ethane from biomass at high temperatures. Gasification aims to produce syngas from biomass, with carbon and hydrogen as the primary components. Syngas can be used as a hydrogen source in various applications, including fuel cells and ammonia production. Syngas can be converted via Fischer-Tropsch (FT) synthesis into liquid hydrocarbons. Further, syngas can be easily used to produce high-value chemicals. In summary, the gasification process provides an alternative approach to utilizing sustainable and renewable resources (Tezer *et al*. 2022).

Europe is the most advanced region in biogas technology. Germany has the highest number of rural biogas projects in the world. Sweden is the leading country in biogas purification for vehicle use. Denmark is known for its distinctive centralized biogas project (Pavičić *et al*. 2022). Large-scale biogas projects have seen rapid development in China, with heat and power cogeneration becoming common models.

3.1.2 Biodiesel

Liquid biofuel has become the most promising alternative fuel. In transportation, liquid biofuels offer valuable zero-carbon solutions, of which biodiesel and bio-jet fuel are the focus of research.

The first generation of biodiesel is the esterification of animal and plant oils (fatty acid triglycerides) and alcohols under the catalysis and chemical reactions to obtain fatty acid methyl esters. However, due to the low combustion value and high freezing point of the first-generation biodiesel, the use scenario is limited and it can only be added and used in a particular proportion (usually 20 per cent). Currently, ester-based biodiesel is mainly used in land transportation and mixed with fossil diesel. In addition, it is also the raw material for a variety of bio-based chemical raw material products. Hydrocarbon-based biodiesel, known as the second generation of biodiesel, takes animal fats extracted from used cooking oils and non-edible corn oil as raw materials and is produced by hydrogenation, isomerization and fractionation. Hydrocarbon-based biodiesel is an actual hydrocarbon, meeting the American Society of Testing Materials (ASTM) International Diesel Fuel Oil Standard (D975), and is known as the “low-carbon twin of petroleum diesel”, able to reduce GHG emissions by 80 per cent. The third generation of biodiesel is to broaden the selection of raw materials, usually using lipids from microorganisms, especially microalgae and yeast. Still, because of the difficulty of extraction and separation, the current technology is under development, accounting for less than 2 per cent of the world. However, it has a higher carbon emission reduction effect, the raw materials do not occupy arable land, there are no scale restrictions and it is a preparation process with long-term development potential (Pydimalla *et al*. 2023).

Biodiesel has no advantage over traditional petrochemical diesel in the combustion stage, but plants absorb CO_2 through photosynthesis during the growth process in the production stage, which significantly reduces the CO_2 emissions of biodiesel in the whole life cycle. However, scientists have found that the carbon reduction effect of some plant-based biodiesel is worse than expected and that the carbon emissions of the entire life cycle will even exceed that of petrochemical diesel. The carbon emission calculation of plant-based biodiesel mentioned above only considers the carbon emissions directly related to production during the life cycle (planting, transportation, preparation, usage) and does not take indirect carbon emissions into account (land-use change, chemicals). For example, when demand for plant-based biodiesel increases, farmers cut down more of their forests for arable land, a process known in the EU as indirect land-use change (ILUC). ILUC releases CO_2 in the form of forest carbon sinks into the atmosphere, greatly increasing the carbon emissions in the whole life cycle of biodiesel. In the case of ILUC, the life cycle carbon emissions of vegetable oil-based oils will exceed those of traditional petrochemical diesel, which is one of the major reasons why the EU is preparing to restrict vegetable oil-based biodiesel (Overmars *et al*. 2011). In addition, the cost of biodiesel is higher than conventional petrochemical diesel, which will further hinder the development of biodiesel without subsidy in the current circumstance (Gebremariam and Marchetti 2018).

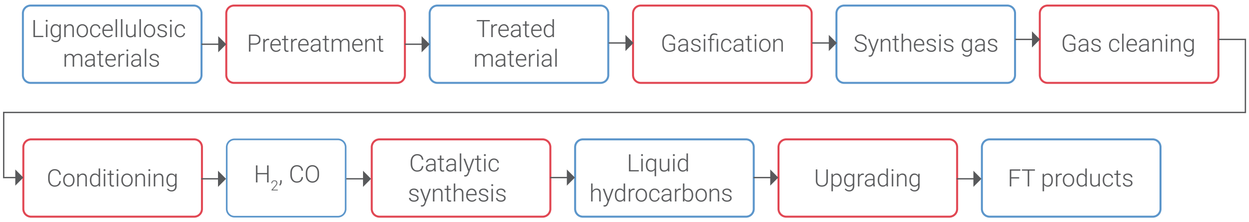
3.1.3 Bio-jet fuel

With the rapid development of the aviation industry and the continuous increase in air traffic, the global demand for jet fuel is growing rapidly. Also, the electrification of the aviation industry does not seem techno-economically feasible. Using bio-jet fuel produced from biomass can alleviate the pressure of fossil energy and reduce GHG emissions. Bio-jet fuel refers to the jet fuel formed directly or indirectly by using biomass raw materials, and most of the bio-jet fuel is mixed with fossil jet fuel in a volume fraction of less than 50 per cent. Compared with fossil jet fuel, bio-jet fuel has low sulfur content, high thermal stability and good low-temperature fluidity. It is compatible with the fuel system of conventional engines and can be used directly in aircraft engines without modification. Australia, the USA and many European countries are actively promoting the application of bio-jet fuel. China, Japan, the United Arab Emirates and other countries are also piloting or planning the development of bio-jet fuel (Wei *et al*. 2019).

ASTM first proposed the certification for sustainable aviation fuel for testing and materials. In 2009, ASTM-approved fuels produced by the FT process as the first biofuel for commercial flight use. There are also some other pathways being certified to complete the specification. At present, the main technologies include FT, hydroprocessed esters and fatty acids (HEFA), synthesized iso-paraffins (SIP) and alcohol-to-jet (ATJ).

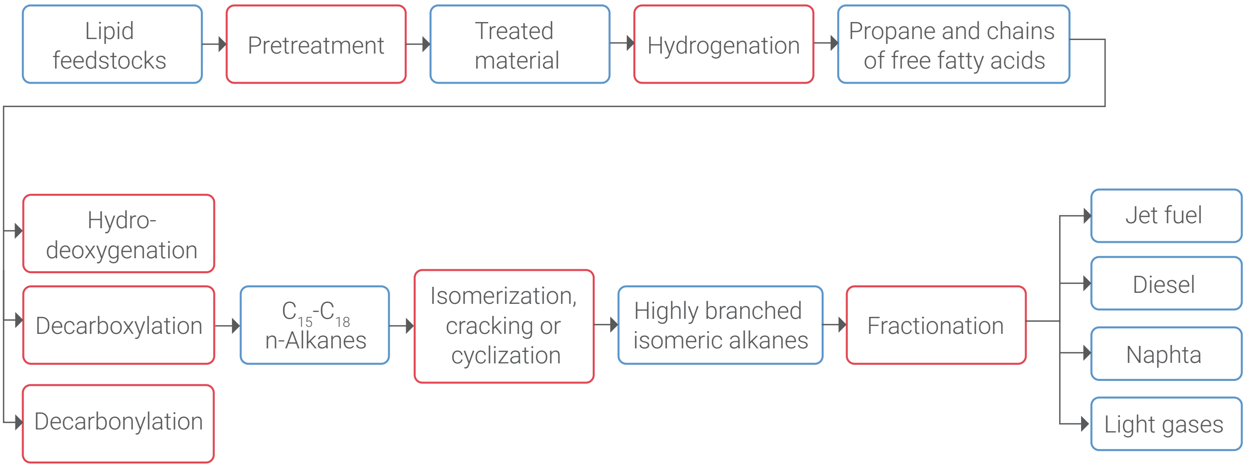
The FT pathway is a conversion technology comprising biomass gasification, cleaning and conditioning of the produced synthesis gas, and subsequent synthesis to obtain liquid biofuels. A general process flow for FT pathways is shown in Fig. 3.2.

Fig. 3.2 General process flow FT pathway



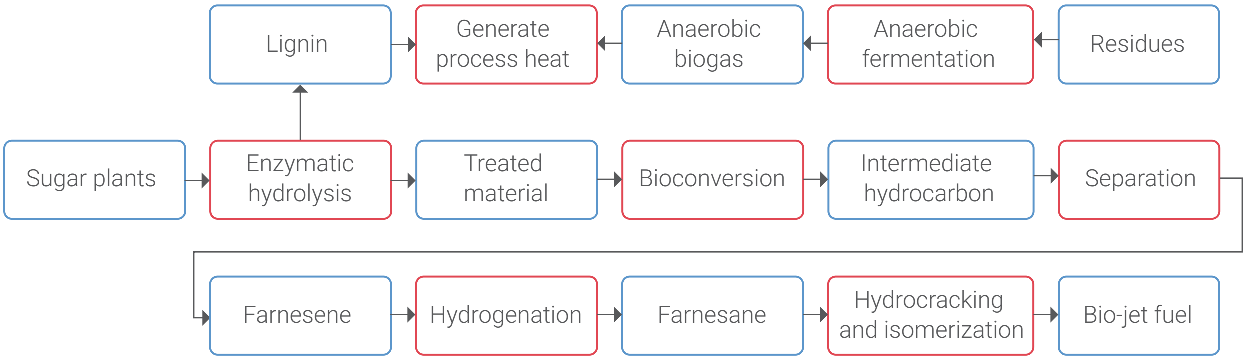
The HEFA pathway is a high maturity level and commercially available conversion technology. The HEFA pathway consists of hydroprocessing lipid feedstocks to upgrade them to drop-in jet fuels. The whole process flow for HEFA pathways is shown in Fig. 3.3.

Fig. 3.3 General process flow HEFA pathway



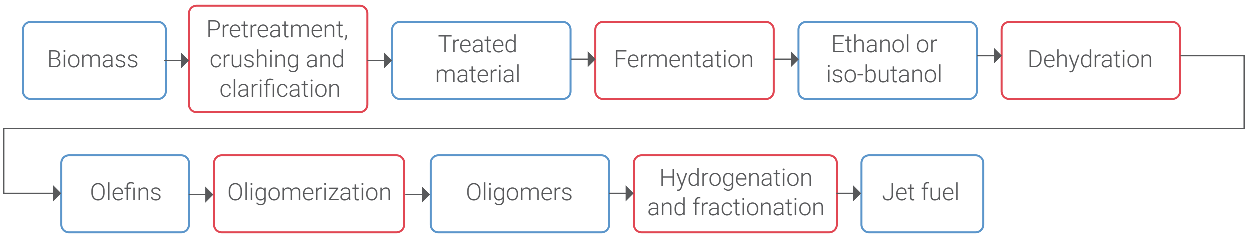
The SIP pathway is a biochemical conversion technology. Microorganisms synthesize a hydrocarbon molecule called farnesene which can be upgraded to farnesane. Farnesane can be blended with petroleum-derived fuel. The general process for this pathway is shown in Fig. 3.4.

Fig. 3.4 General process flow SIP pathway



The ATJ pathway is a biochemical conversion process for producing jet fuel blend stock from alcohols. ATJ offers opportunities for alcohol producers to enter the aviation market. A general process description for the ATJ pathway is shown in Fig. 3.5.

Fig. 3.5 General process flow ATJ pathway



The minimum price of most bio-jet fuels is higher than that of conventional jet fuels. Raw material costs, equipment costs and operating costs greatly impact the price of bio-jet fuel. Studies have shown that raw material costs can account for 80 per cent of the total cost of HEFA jet fuel (Wei *et al*. 2019). The price of ATJ jet oil mainly depends on the preparation process of alcohol, and the different preparation processes and the raw materials greatly influence the price of ATJ. The proportion of the FT method's fixed asset cost is very large. However, because the FT method can handle a variety of raw materials (biomass, municipal solid waste, etc.) and some raw materials (e.g. municipal solid waste) have almost no cost, the price of FT jet fuel is relatively low, and the price fluctuation is relatively small (Wei *et al*. 2019).

3.1.4 The development of biodiesel and bio-jet fuel

The international community increasingly emphasizes energy security, environmental protection, and accelerating the development and utilization of renewable energy sources like biomass energy.

Regarding the feedstock structure, plant oils remain the primary raw materials for biodiesel production. Waste oil accounts for only 10 per cent of the raw material (International Energy Agency 2024). Used cooking oil methyl ester achieves a GHG emission reduction of 83 per cent. Gradually increasing in its competitiveness, used cooking oil methyl ester biodiesel from waste oils and fats has become the second-largest biodiesel feedstock in Europe, accounting for 23 per cent of biodiesel feedstock, primarily imported from China.

Currently, biodiesel production and demand are significantly influenced by the biodiesel policies of various countries. However, because of the restrictions imposed by the EU on biodiesel made from plant oils, plant oil demand is expected to slow down in 2023, but it is still anticipated to continue growing by 2030, driven by demand from other regions (Fang, Smith Jr. and Qi eds. 2017). Biodiesel offers environmental benefits and carries notable advantages in terms of energy density and adaptability to engines and refinery facilities. It is the simplest and most effective form of energy to supplement and replace petroleum products. The development of biodiesel plays a positive role in helping reduce carbon emissions, supplementing petroleum demand and ensuring energy security.

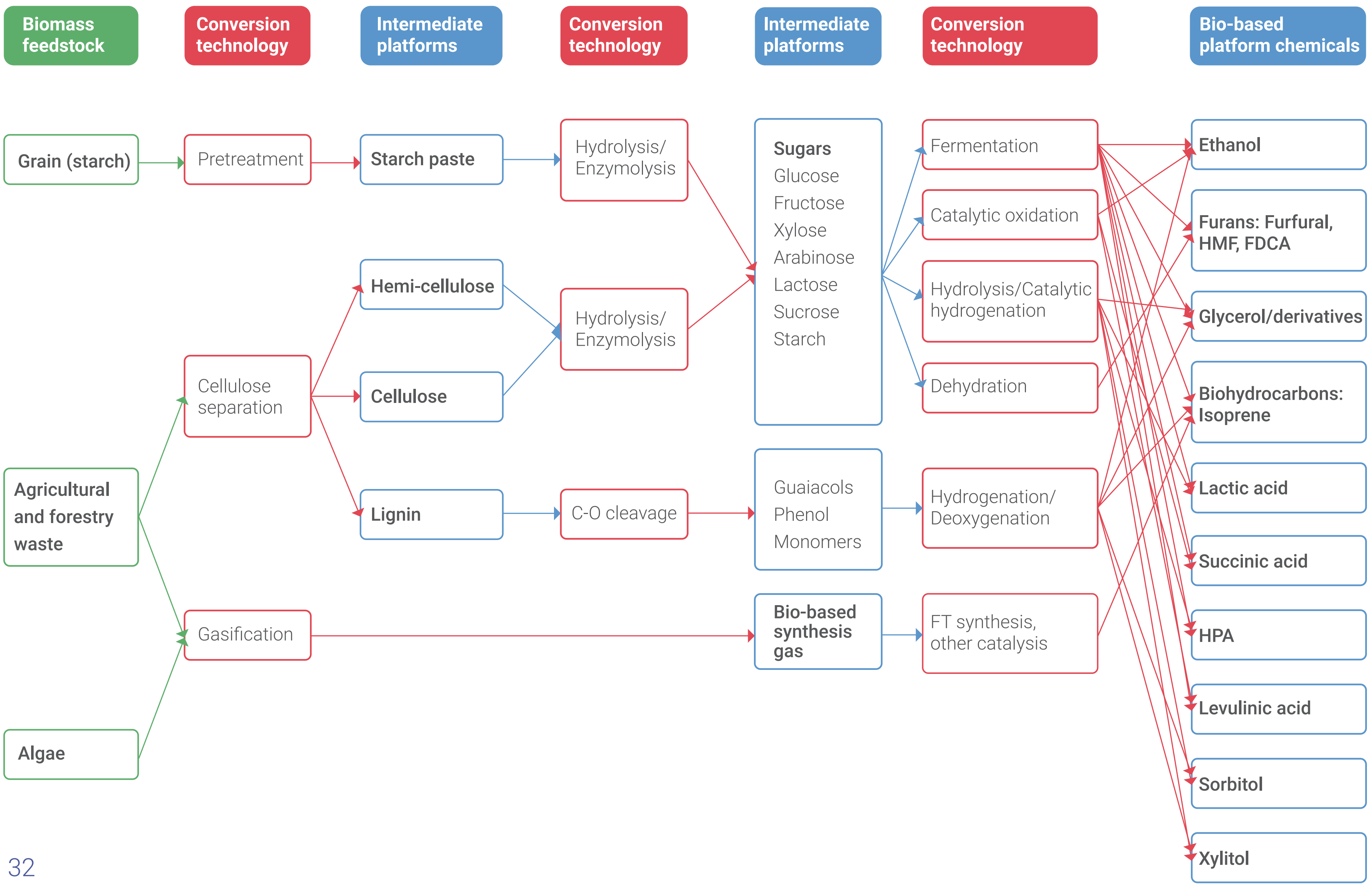
Globally the development of bio-jet fuel remains in its early stages. It will eventually become a solid complement to petroleum-based aviation kerosene, with vast development prospects. According to publicly available information from the International Civil Aviation Organization, countries like the USA, Canada and Finland have established a scaled-up market for aviation biofuels, building a complete industry chain. In China, energy companies have completed two verification flights and two passenger-carrying commercial flights using bio-jet fuels. The commercial application of bio-jet fuels is gaining momentum. Looking at the supply and demand data, bio-jet fuels production and consumption are growing rapidly, and with the increasing stringency of aviation industry carbon reduction policies, the situation has shifted from surplus supply to tight supply, with demand for bio-jet fuels gradually increasing, (Hao *et al*. 2019). Only HEFA synthetic paraffinic kerosene (HEFA-SPK) have reached maturity and commercialization. It is anticipated that HEFA-SPK will be the primary bio-jet fuel in the short term. In the short term, it is challenging for bio-jet fuel prices to compete with traditional aviation fuels. Therefore, policy support and technological advancements are necessary to make bio-jet fuels competitive.

As countries advance their industrialization levels, their energy structures are undergoing transformations. Developed countries with the highest levels of industrialization have entered a phase of reindustrialization. Biomass energy, a carbon-neutral and clean renewable energy source, has already attained a substantial share in their energy portfolio. In contrast, developing countries are in the middle-to-later stages of industrialization and face the dual challenges of economic growth and environmental pollution. The biomass energy industry has received some development opportunities in these countries, but it has only achieved preliminary industrialization in specific sectors and still lacks market competitiveness. The least developed countries are generally in the early stages of industrialization, and biomass energy constitutes a significant portion of their energy structure. However, this utilization is often in traditional, low-efficiency forms. In summary, as the fourth-largest energy source in the world's total energy consumption, biomass energy is considered a favourable choice for countries in their energy transition and development because of its carbon reduction and clean energy characteristics.

3.2 Bio-based platform chemicals

To reduce reliance on fossil resources and replace petroleum-based chemicals, converting biomass into critical platform compounds through diverse technological routes is essential. The advancement of cost-effective and sustainable conversion processes is of huge importance.

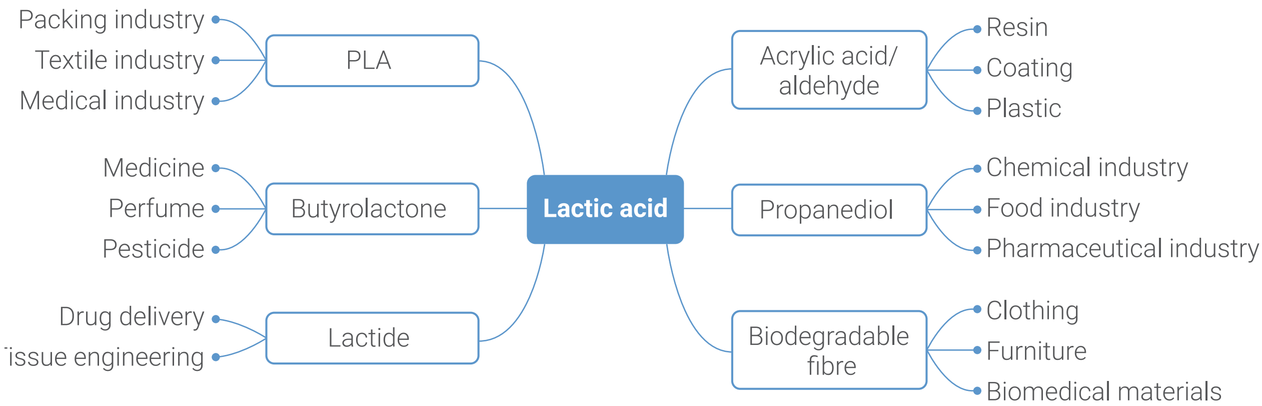
Fig. 3.6 Bio-based platform chemicals flow chart for biomass feedstocks



3.2.1 Bio-based acids

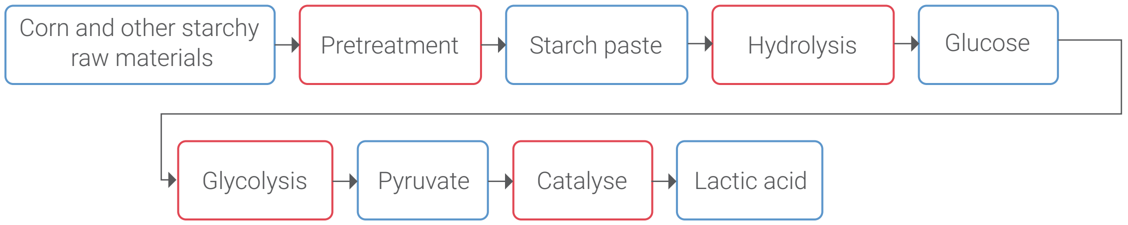
Organic acids are essential commodities widely used in food and the chemical industry. Lactic acid, one of the world's top three organic acids, is a significant bio-based platform chemical. It can be converted into materials such as PLA, coatings, resins, solvents and fragrances through biological/chemical transformations.

Fig. 3.7 Lactic acid as a platform chemical



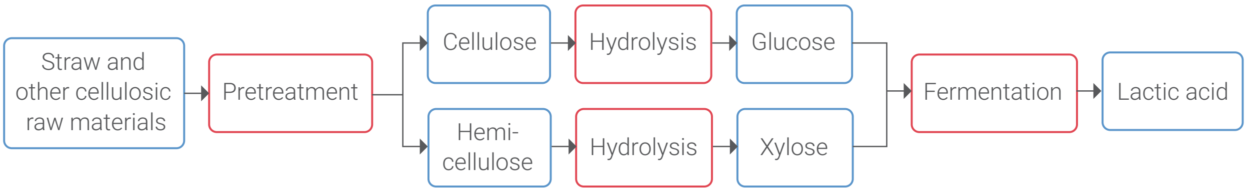
Lactic acid can be synthesized from starches such as corn or cellulose from straw, typically through glucose or cellulose hydrolysate fermentation using microorganisms or cell-catalysed processes. The fermentation of starch-based raw materials like corn is relatively mature, and the exploration of fermenting lactic acid from straw as a raw material using synthetic biology techniques shows promise.

Fig. 3.8 Production of lactic acid from biomass



The current challenges primarily lie in the efficient removal of inhibitory substances in straw, hindering its industrial-scale application. In the future, constructing microorganism strains through synthetic biology for sugar assimilation fermentation to produce lactic acid could enhance production efficiency.

Fig. 3.9 Production of lactic acid from lignocellulosic biomass

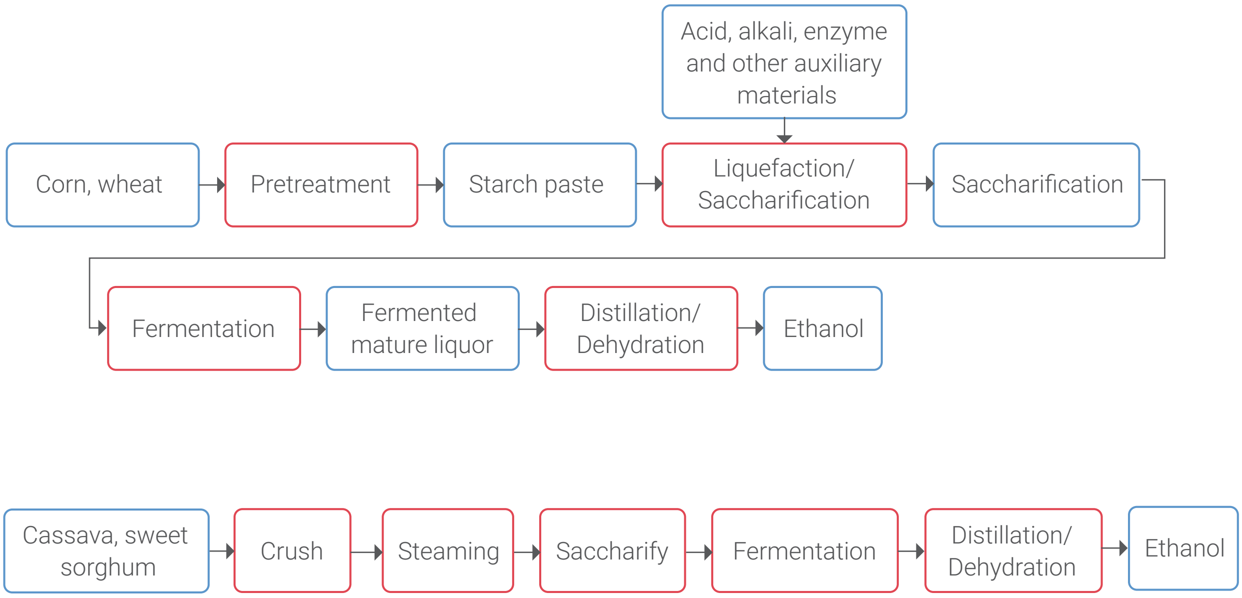


3.2.2 Bio-based alcohols

The technological advancement of ethanol enhances its potential as a raw material for chemical production. Ethanol and related alcohols are precursors to dehydrated olefins and can also substitute for methyl tertiary-butyl ether, contributing to reduced carbon, CO_2, nitric oxide and nitrogen dioxide emissions.

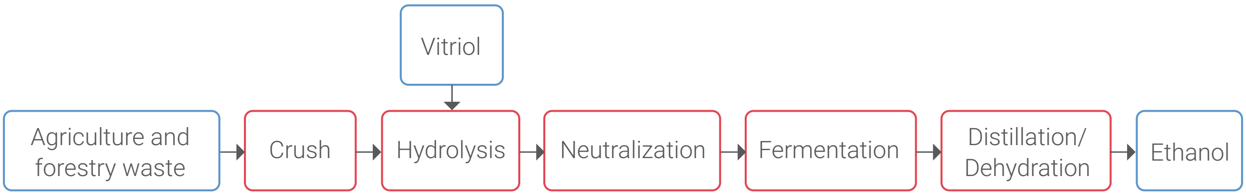
Currently, grain ethanol production from food crops and non-grain ethanol from non-food crops pose issues related to competition with human and animal food sources and land-use conflicts. However, cellulosic ethanol production from agricultural and forestry waste like straw can enhance resource utilization, offering promising market prospects.

Fig. 3.10 Production of grain ethanol and non-grain ethanol from biomass



Cellulosic ethanol production involves three primary process configurations: separate hydrolysis and fermentation, simultaneous saccharification and (co)fermentation, and consolidated bioprocessing (Fang, Smith Jr. and Qi eds. 2017).

Fig. 3.11 Production of cellulosic ethanol from lignocellulosic biomass

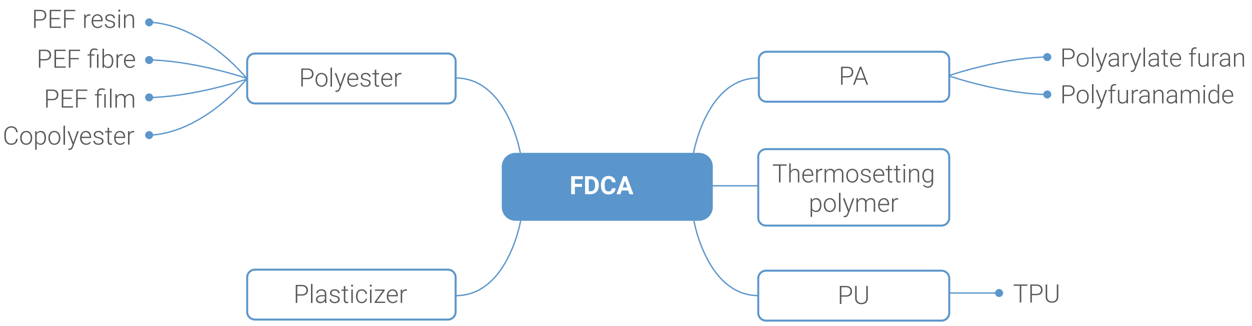


Because of the inherent structural impediments of lignocellulosic biomass, the utilization and development of more robust fermentation microorganisms are crucial. Further, the utilization of processes such as synthetic gas-based bioprocessing for ethanol production represents a promising avenue for non-food ethanol production in the future (Wang *et al*. 2022).

3.2.3 Bio-based furans

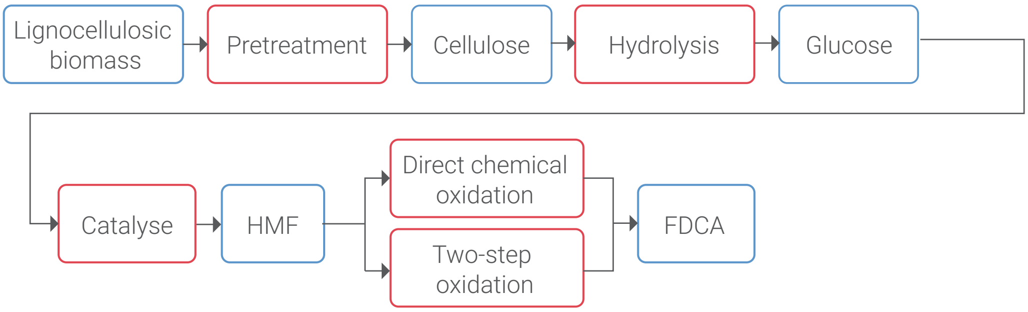
2,5-Furandicarboxylic acid (FDCA) finds extensive applications in numerous fields, particularly as the most promising alternative to terephthalic acid (PTA), garnering widespread attention. The synthesis routes for FDCA primarily include the HMF route, the sugar acid route, the glucaric acid route and the diglycolic acid route, among others (Zhao *et al*. 2023). The HMF route is currently the most prominent and has made significant progress, with the potential to lead in industrial-scale production.

Fig. 3.12 FDCA as a platform chemical



However, HMF synthesis presents challenges, such as multiple side reactions, difficult separations and HMF's instability, resulting in higher costs. Additionally, while numerous studies have explored the conversion of HMF to FDCA, such as catalysis by noble metal catalysts like Pt, there still exists a lack of a cost-effective, efficient and stable catalytic oxidation system (Fang, Smith Jr. and Qi eds. 2017). Therefore, the efficient and green conversion of cellulose into high-purity HMF, along with the development of inexpensive catalytic systems for the conversion of HMF into FDCA, stands as a key focus of future research.

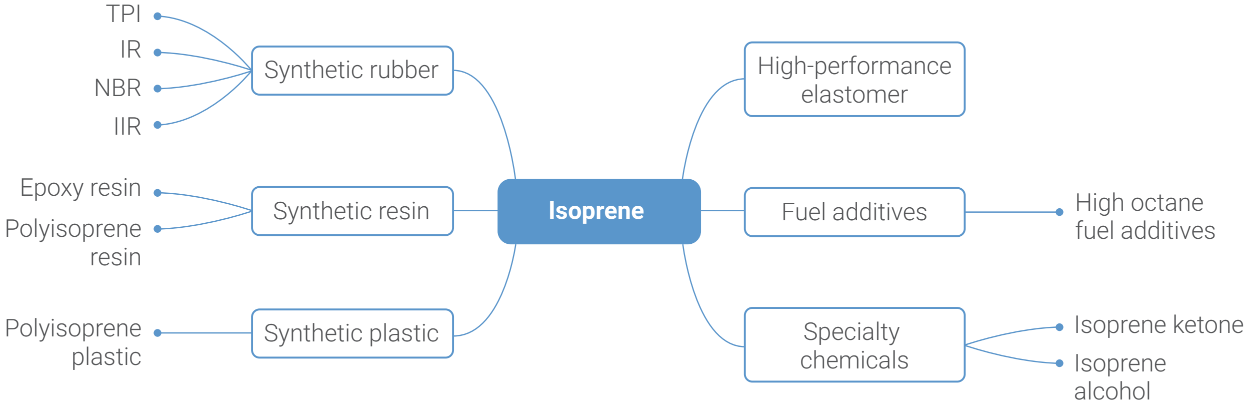
Fig. 3.13 Production of FDCA from lignocellulosic biomass



3.2.4 Bio-based hydrocarbons

Isoprene is a high-value hydrocarbon compound that has gained significant attention as an essential chemical raw material. It is primarily utilized as a monomer or copolymer in synthesizing synthetic rubber and finds applications in the production of pesticides, pharmaceuticals, fragrances and other products.

Fig. 3.14 Isoprene as a platform chemical



Presently, the majority of isoprene is predominantly derived from thermal cracking processes. Recently, there has been a growing focus on biologically synthesizing isoprene. This includes the achievement of high-purity isoprene through engineered Escherichia coli fermentation (Whited *et al*. 2010) and cultivating cells capable of isoprene synthesis from biomass. Additionally, research suggests that bio-based isoprene is now cost-competitive with petroleum-based counterparts, highlighting its potential as a substitute for petrochemical feedstocks (Xiao 2020).

3.2.5 Summary and prospect

Bio-based platform chemicals are currently a focal point of attention, as the long-term perspective suggests that all materials produced from fossil resources today can potentially be synthesized from biomass. Technological trends are gradually transitioning from starch-based to lignocellulosic feedstocks. Utilizing waste biomass as a raw material circumvents resource competition and land disputes related to traditional grain production, offering significant overall benefits.

From a cost perspective, global annual waste biomass production provides an economically efficient feedstock for bio-based platform chemical production. Advances in biotechnology have substantially reduced production costs, making high-value product manufacturing more cost-effective and competitive. Technically, challenges exist in lignocellulosic biomass conversion due to plant cell wall resistance to microbial and enzymatic deconstruction (Dessie *et al*. 2019). However, genetic engineering and synthetic biology have lowered technical barriers, creating opportunities for lignocellulosic synthesis pathways' development (Bourdon *et al*. 2023). This enables more efficient cellulose breakdown and precise compound production, making commercial bio-based platform chemical production feasible. Utilizing waste biomass for bio-based platform chemicals yields dual environmental benefits by reducing petroleum-based chemical synthesis, minimizing pollution and addressing the incineration of agricultural and forestry waste.

The global bio-based chemicals industry is advancing towards scalability and industrialization. The development of bio-based platform chemical synthesis, especially utilizing waste biomass, propels sustainable chemical manufacturing and high-value product production. Future efforts should focus on optimizing technology integration, leveraging mature key technologies like cellulose pretreatment, enzyme formulations and pentose fermentation to drive further advancements and contribute to environmental, economic and social sustainability.

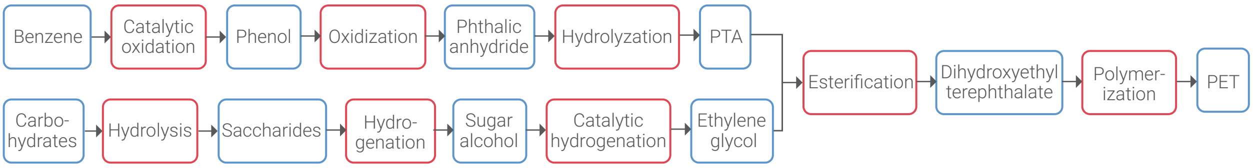
3.3 Bio-based plastics

This section describes the production processes of the 12 most common bio-based plastics on the market. Since PA and PHA products are too diverse to be generalized and starch blends are not monolithic in composition, their production process routes are not presented.

3.3.1 Bio-based PET

PET is chemically prepared by esterifying PTA and ethylene glycol to synthesize bis (2-hydroxyethyl) terephthalate and then undergoes a polycondensation reaction to produce a crystalline saturated polyester. PET downstream applications in a wide range of areas belong to the five major engineering plastics. It is mainly used in the field of electrical and electronic appliances such as electrical sockets and electronic connectors. In addition, PET can also be spun into polyester fibre and used in film for audio, video, movie film, substrate, insulation film, product packaging and more. The production technology is shown in Fig. 3.15.

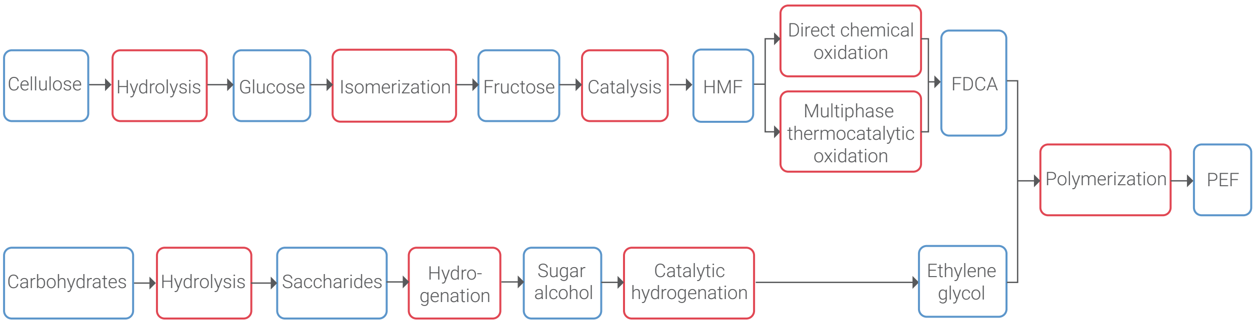
Fig. 3.15 Production process of PET



3.3.2 Bio-based PEF

PEF is produced from FDCA, obtained by hydrolysis and oxidation of starch or cellulose from abundant sources. FDCA and ethylene glycol polycondensation can be obtained from bio-based aromatic polyester PEF. The aromaticity and electron conjugation effect of the furan ring structure contributes to the synthesis of high-performance polymeric materials with excellent physical and mechanical properties within a specific temperature range. Therefore, PEF exhibits outstanding electrical insulation properties, resistance to creep, fatigue resistance, friction resistance and dimensional stability. However, its corona resistance is relatively poor. The production technology is shown in Fig. 3.16.

Fig. 3.16 Production process of PEF



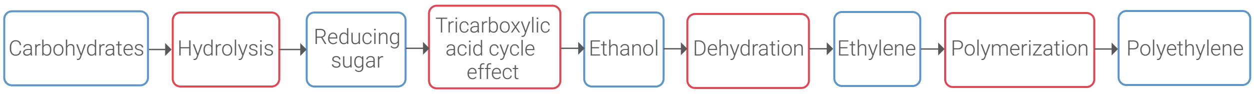
3.3.3 Bio-based PA

Polyamide (PA) is a linear polymer with an amide structure in the main chain. The main products include aliphatic PA, aromatic PA and semi-aromatic PA (such as PA 6, PA 66, PA 610, PA 6T, PA 11, PA 46, PA 10, etc.). PA has good mechanical properties, heat resistance, abrasion resistance, chemical resistance, corrosion resistance and self-lubrication, a low coefficient of friction, a certain degree of flame retardancy, and self-extinguishing properties. PA material's excellent performance makes it widely used in industry in electronic and electrical appliances, automotive, mechanical components, medical and pharmaceutical fields.

3.3.4 Bio-based polyethylene

Polyethylene is a polymer made of ethylene as a monomer through free radical polymerization or coordination polymerization, which has the advantages of resistance to acid and alkali, low temperature and chemical stability. Common polyethylene has a high-density polyethylene, low-density polyethylene, linear low-density polyethylene, and more. In addition to good mechanical properties and processing performance, high-density polyethylene also has excellent hygiene, barrier, corrosion resistance, insulation and more, and is commonly used in pipelines, hollow film and wire and cable. The material of low-density polyethylene is soft, so it is commonly used in plastic bags, agricultural film, etc. Linear low-density polyethylene is used primarily in agricultural film, packaging film, wire and cable, tubing, coated products and so on. The production technology is shown in Fig. 3.17.

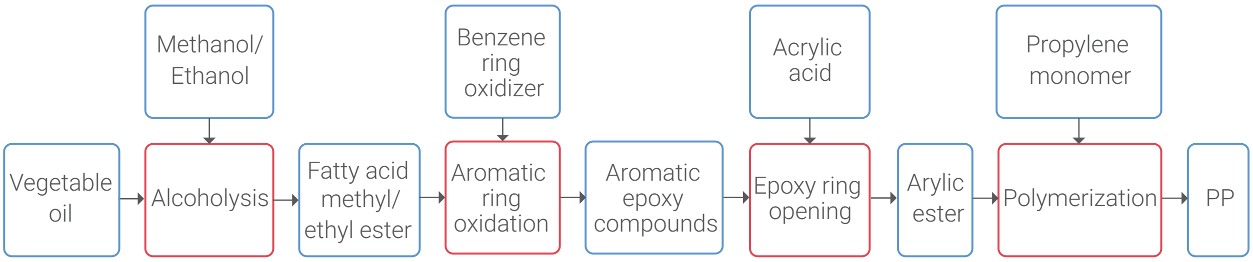
Fig. 3.17 Production process of polyethylene



3.3.5 Bio-based PP

PP is a polypropylene material prepared from biomass feedstock. While conventional polypropylene is prepared from petroleum-derived chemical feedstocks, bio-based polypropylene uses renewable resources such as vegetable oils and cellulose as feedstocks. It has similar properties and application areas as chemical-based polypropylene, with good mechanical properties, chemical resistance, and low-temperature impact resistance. Therefore, bio-based polypropylene can be used in plastic products, packaging materials, medical devices, and other fields. The production technology is shown in Fig. 3.18.

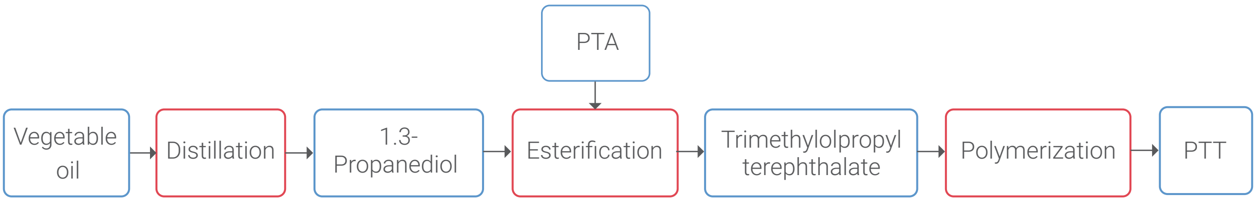
Fig. 3.18 Production process of PP



3.3.6 Bio-based PTT

PTT is produced by the esterification and polycondensation of PTA and 1,3 propanediol. Ninety per cent of the downstream of PTT is used to synthesize PTT fibres, while ten per cent is used in engineering plastics. It has excellent heat resistance, solvent resistance and mechanical strength. It can be used to manufacture various products such as textiles, packaging materials and electronic product casings. In addition, because of its good dyeability, moulding and injection moulding, bio-based PTT plastics are also widely used in automotive parts manufacturing and wear-resistant industries. The production technology is shown in Fig. 3.19.

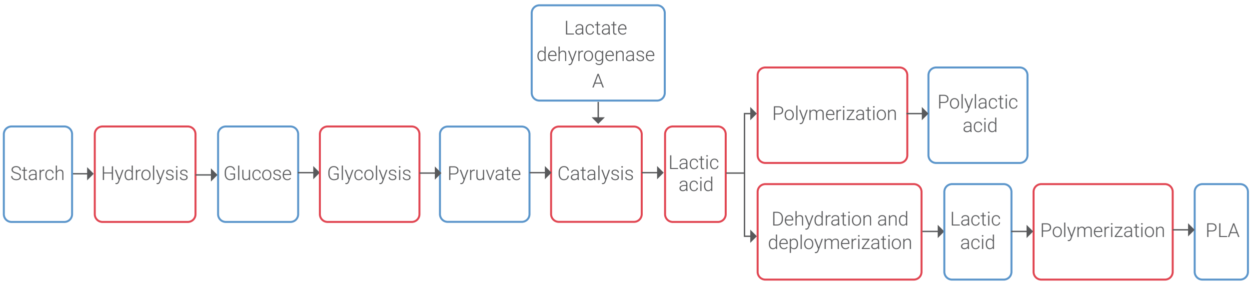
Fig. 3.19 Production process of PTT



3.3.7 Bio-based polylactic acid

The monomer raw material of PLA is lactic acid. There are two main methods for the synthesis of PLA: the direct polycondensation of lactic acid and the ring-opening polymerization of propylene glycol ester (also known as a two-step process). The two-step method is the most commonly used. It begins with lactic acid distillation under reduced pressure to produce lactide. PLA is then prepared by using lactide as monomer under the condition of initiator, high temperature and high vacuum for several hours. The production technology is shown in Fig. 3.20.

Fig. 3.20 Production process of PLA



3.3.8 Bio-based polyhydroxyalkanoates

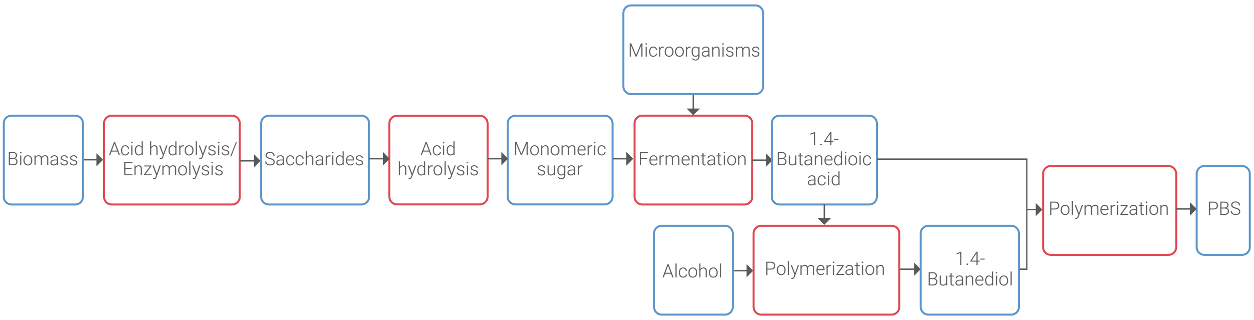
PHA monomers are generally 3-hydroxy fatty acids, and the diversity of monomers leads to the variety of PHA types. There are many ways to classify PHA. The length of the monomer's carbon chain can be divided into short-chain PHA, medium-long-chain PHA, and short-chain and medium-long-chain co-polymerized PHA. And according to the polymerization mode, it can be divided into homopolymer, random copolymer and block copolymer. The diverse structure, biodegradability, biocompatibility and renewable resource synthesis of PHA make it widely used in chemical products, medical implant materials, drug slow-release carriers, fuels and other fields.

PHA can only be synthesized in the cell body and used as a synthetic material. The synthesis pathways include the glycolysis pathway, tricarboxylic acid cycle, fatty acid biosynthesis initiation pathway, fatty acid biosynthesis prolongation pathway and so on.

3.3.9 Bio-based polybutylene succinate

PBS is a commercially available biodegradable aliphatic polyester synthesized by 1,4-butanedioic acid and 1,4-butanediol polycondensation. It is widely used in food packaging, bottles, supermarket bags, sanitary products, mulch film and compost bags, drug release carriers, tissue engineering scaffolds and other biomaterials. Because of the large number of ester bonds in the molecular chain, PBS can be easily metabolized and decomposed by the enzymes of various microorganisms or plants and animals in nature and ultimately converted into water and CO_2. The production technology is shown in Fig. 3.21.

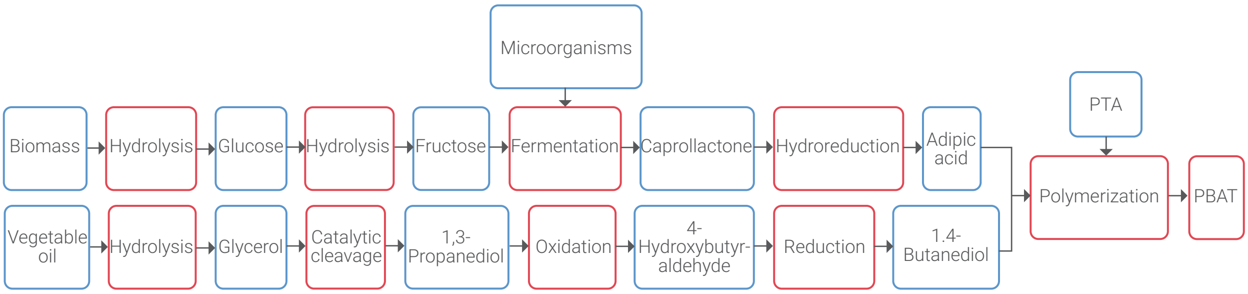
Fig. 3.21 Production process of PBS



3.3.10 Bio-based polybutylene adipate terephthalate

PBAT is one of the best applied in the market. Currently, most PBATs are produced from fossil-based raw materials, but a small number of bio-based products can be produced from biomass raw materials. PBAT is produced from pure PTA, adipic acid, bio-based 1,4-butanediol, bio-based adipic acid as raw materials, and esterification and polycondensation reactions are carried out directly under catalyst conditions. PBAT has good thermal and mechanical properties including good transparency, high toughness, and anti-impact qualities, and is mainly used for preparing thin-film products, which are widely used in the fields of packaging and agriculture. The production technology is shown in Fig. 3.22.

Fig. 3.22 Production process of PBAT



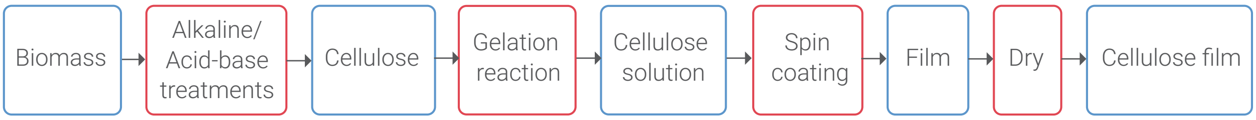
3.3.11 Starch blends

Starch is a promising material as it is a low-cost, highly available natural biopolymer and fully biodegradable, low-cost, and renewable. It is used to produce edible biodegradable packaging and is an attractive alternative to synthetic polymers. Starch blends are chemically modified starch using chemical reactions to reduce the hydroxyl groups of starch and change its original structure, thereby altering the starch's corresponding properties and turning the original starch into a thermoplastic starch. It is one of the biodegradable plastics that have undergone the longest research and development had the most mature technology, the largest scale of industrialization and the highest market share.

3.3.12 Cellulose films

Cellulose film is a biomass-based biodegradable membrane material prepared from natural plant cellulose. It possesses a high transparency, strong oxygen barrier, high-temperature resistance, anti-static and more. Cellulose film is widely used as packaging materials for food, medicine, express delivery, takeaway and many other fields. The production of cellulose films consists of the following processes: biomass feedstock collection and pretreatment, alkaline/acid-base treatment, cellulose gelation, spin coating and dry. The production technology is shown in Fig. 3.23.

Fig. 3.23 Production process of cellulose films



3.3.13 Summary and prospect

Bioplastics are anticipated to expand as a promising alternative, especially for biodegradable plastics. In the face of resource shortage, climate change and plastic pollution, there has been a shift from petrochemical to bio-based plastics.

From a cost perspective, cost-effectiveness and applicability are the main constraints limiting the productivity of various bioplastics. Low oil prices, narrow profit margins and existing fossil fuel subsidies reduce the cost-competitiveness of bio-based manufacturers (Garrison 2016). Some firms rely on selling products with higher margins, as in the medical or nutrition areas, to yield the profits needed to scale up bioplastic production. To reduce the production costs of bioplastics, cheap and abundant raw materials such as lignocellulosic wastes, microalgae (Chong *et al*. 2021; Chong *et al*. 2022) and food wastes (Jogi and Bhat 2020) can be an excellent feedstock for the bioplastic industry.

From a technical point of view, the production technology of bio-based plastics has made significant progress in recent years, and their performance is constantly being improved and refined, making them technically viable alternatives. The range of applications is also expanding, including packaging, transportation, automotive, consumer electronics, home and household products, agriculture and gardening, the textile industry, construction and other fields.

Regarding environmental advantages, the raw materials for bio-based plastics come from renewable resources. Using renewable resources to manufacture plastics reduces dependence on non-renewable resources and lowers the environmental impact of their extraction and processing. In addition, bio-based plastics have lower carbon emissions. Because bio-based plastics are made from natural sources, such as plants, the CO_2 absorbed during their growth makes them low-carbon emitting compared with petroleum-based ones.

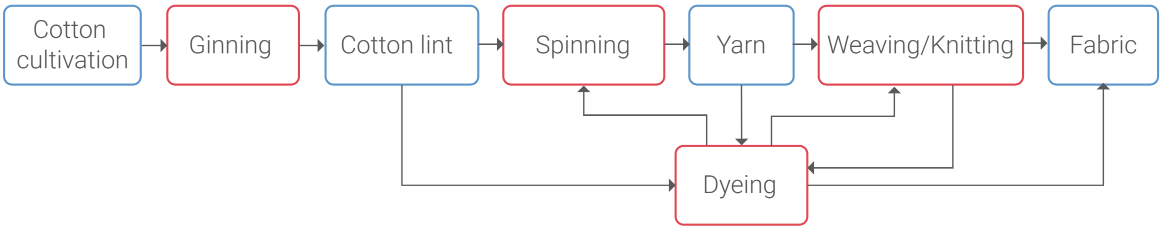
Upcoming regulatory incentives, including the taxation of non-bio-based materials, will further drive the demand for existing and new bioplastics (Rosenboom 2022). Production capacity will continue to develop and diversify over the next few years as novel bioplastics such as PHAs, PEF, bio-PP, and PLA become commercially accessible. Global bioplastic production capacity is expected to expand from approximately 2.22 million tons in 2022 to more than 2.9 million tons in 2025.

3.4 Natural fibre for textile

This section mainly introduces the development status and main technical routes of the typical types of natural fibres – cotton, silk, flax and hemp – to reflect the role of natural fibres in the bio-based circular economy.

3.4.1 Cotton

Fig. 3.24 Production process of cotton textile



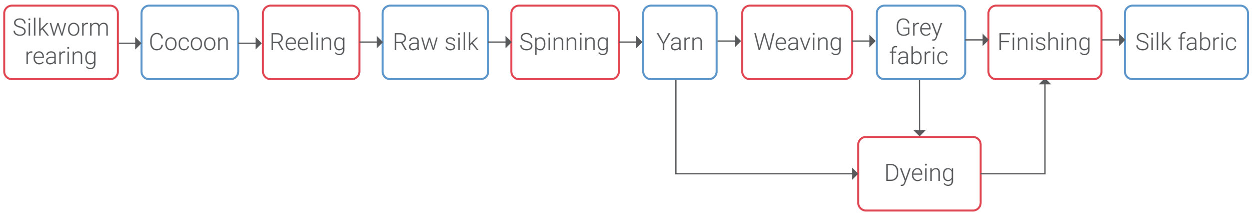
Cotton is by far the most dominant natural fibre, accounting for 80 per cent of natural fibre use, and is widely used in apparel and furniture because of its fast growth rate. Cotton is grown globally on more than 30 million hectares of farmland in 75 countries and regions (Baydar, Ciliz and Mammadov 2015), occupies just 2.1 per cent of the world's arable land and yet meets 25 per cent of the world's textile needs (World Trade Organization 2021). China, India, the USA, Brazil, Australia, Turkey and Pakistan are the world's leading cotton producers, accounting for more than 75 per cent of the world's production (Statista 2023). Global cotton production is expected to reach 30.6 megatons by 2031 (OECD and FAO 2022).

Cotton textiles have a complex life cycle, described in Fig. 3.24, which includes cultivation and several manufacturing steps, mainly composed of ginning, carding, spinning, weaving (or knitting), dyeing and finishing. Cotton and related products provide tens of millions of jobs, especially in developing countries, and are the main source of livelihood and income for millions of rural smallholder farmers around the world, with an average of five jobs per ton of cotton (World Trade Organization 2021).

Cotton consumption has surged into overconsumption in recent years as a result of fast fashion and its promotion, and the ensuing environmental problems have become increasingly acute. For example, inputs of chemical fertilizers and pesticides during cotton cultivation cause non-point source pollution. Cotton cultivation is also water-intensive. Textile production is accompanied by high GHG emissions and releases large quantities of pollutants such as dyes, wetting agents and softeners into waterways (Zhang *et al*. 2023). Additionally, the uneven distribution of cotton cultivation, production and consumption is projected to cause an inequitable distribution of environmental consequences. The EU's textile and clothing industry has a large carbon footprint which is "outsourced" abroad to Brazil, China, India and the Russian Federation (Mair, Druckman and Jackson 2016). As the global cotton trade increases, the major consumers should notice and reduce both inequity and environmental impact.

3.4.2 Silk

Fig. 3.25 Production process of silk textile

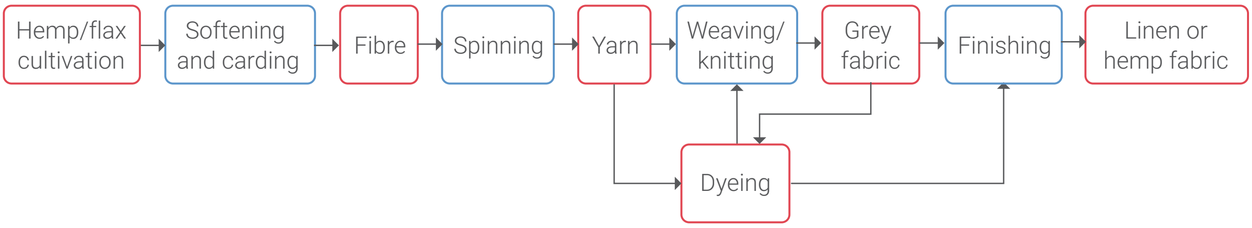


A natural fibre, silk is light, soft and delicate, and is one of the main components of animal protein and contains 18 kinds of amino acids. From the cocoon, silk generally needs to go through more than 10 processes, including reeling, winding, twisting, spinning, weaving, printing and dyeing. Fig.3.25 shows the main process of silk textile production. Although silk accounts for only a small part of the global textile market, its supply chain provides significant employment and income-generating opportunities for rural residents.

The global average annual production of silk exceeds 100,000 tons: China is the world's largest silk producer, followed by India and Uzbekistan (Atlas Big 2019). China, India, the USA and the EU are important participants in the global silk trade. Asia is the main region of silk production, accounting for 90 per cent of global production (International Sericultural Commission 2023). Industrialization of the silk industry, coupled with various government schemes, will boost the production of raw silk in the Asia-Pacific, making the region the largest market during the forecast period.

3.4.3 Bast fibre

Fig. 3.26 Production process of flax and hemp textile



Bast fibre, mainly obtained from flax, hemp and jute, is widely used for textiles and cordage and favoured for its natural, simple and rare colour. Flax has been used by humans for at least 30,000 years; it accounts for 1.5 per cent of the world's total amount of natural fibre. In 2021, the global flax planting area was 241,000 hectares and the global production reached 0.89 megatons. From 1994 to 2021, Europe accounted for more than 75 per cent of the world's flax production, and France was the world's largest producer, followed by China, Belgium and the Russian Federation (FAO 2023).

Hemp is another important textile material. Its production and processing will also have an impact on water resources and the environment; for example, hemp degumming and dyeing processes consume a large amount of fresh water and produce a high concentration of wastewater discharge, with phosphides and sulfides being the main pollutants. However, flax and hemp can be grown with less irrigation and use far fewer pesticides than cotton because they are resistant to many insects and pests (Kozlowski and Muzyczek 2023). In addition, flax and hemp fibres have a relatively long lifespan due to their strength and durability, helping to reduce the life cycle carbon footprint (Liu, Li *et al*. 2023). Given the above characteristics, they are considered one of the reliable options for sustainable textile materials.

3.4.4 Summary and prospect

Natural fibres account for approximately one third of the total textile fibres but are increasingly popular among consumers worldwide because of their biodegradability and renewability, making them an important part of the fibre market. However, the natural fibres, especially cotton, in the planting stage inevitably have problems such as the occupation of arable land, water consumption and pesticide and fertilizer use, which may exacerbate the pressure on land and water resources in the planting area and cause ecosystem damage, among others. Organic cotton cultivation and sustainable farmland and forest management have been found effective to solve the above problems. At the same time, the price-cost squeeze faced as a result of stagnant retail prices and rising production costs is the main challenge facing natural fibre producers, and it is necessary to promote the industry's sustainable development by strengthening innovation and policy support, among others.

With the continuous progress of textile technology, the quality, performance and production efficiency of natural fibres can be significantly improved. New technologies such as nanofibres, nanocellulose and functional coatings can open up new application areas for natural fibres. In addition to the traditional fibres mentioned above, some emerging fibres such as bamboo and wood fibre, because of their superior sustainability, have also entered the textile fibre market, which provides a new option for the realization of the sustainable development of textile fibres.

3.5 Pulp and paper products

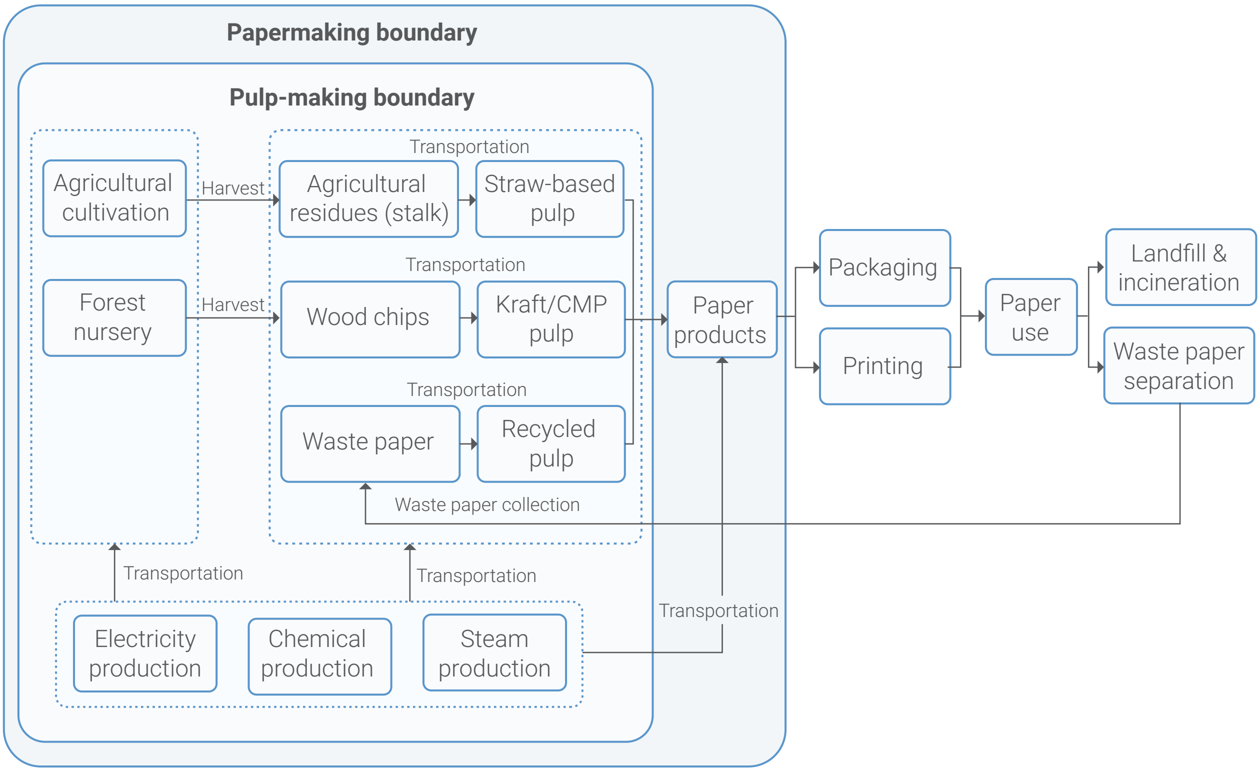
This section mainly introduces the main pulp product process, the future development of pulp products and influencing factors.

3.5.1 Process for pulp and paper production

Pulp and paper mills encompass a highly intricate set of processes involving stages like wood preparation, pulping, chemical recovery, bleaching and papermaking, all working in tandem to transform wood and other cellulose sources into the final product. The intended end product often dictates the choice of processing methods and the type of wood utilized. The pulp used in paper production can be derived from either virgin fibre through chemical or mechanical means or obtained by repulping recycled paper. Wood is the primary source material, while recycled paper constitutes approximately 50 per cent of the fibre input. Materials like straw, hemp, grass, cotton and other cellulose-bearing substances can also be employed in certain instances. The paper production process essentially comprises two main steps: the fibrous raw material is converted into pulp, then the pulp is transformed into paper. Initial processing of harvested wood is carried out to extract fibres from the unneeded lignin. Fig. 3.27 shows the distinct process areas of producing paper or paperboard.

Pulp production can be achieved through mechanical or chemical means. Subsequently, the pulp undergoes bleaching and further treatment, contingent on the intended type and quality of the paper. The pulp is dried and compressed within the paper factory to form paper sheets. An increasingly significant portion of paper and paper products undergo recycling in the aftermath of use. Non-recycled paper is disposed of through landfilling or incineration.

Fig. 3.27 The process of pulp and paper production



Source: Adapted from Sun *et al*. (2018).

Table 3.1 Steps involved in the manufacturing of pulp and paper

Operation	Processes
Raw material preparation	Debarking
Pulping	Chipping and conveying
	Chemical pulping
	Semi-chemical pulping
	Mechanical pulping
	Recycled paper pulping
Chemical recovery	Evaporating
	Recovery boiler
	Recausticizing
	Calcining
Bleaching	Mechanical or chemical pulp bleaching
Stock preparation and papermaking	Preparation of stock
	Dewatering
	Pressing and drying
	Finishing

3.5.2 Process of wood

Wood is transported to the mills from the logging site via truck, rail, or ship/barge and is received in the wood yard in the form of logs or chips. Logs are typically delivered with their bark intact and must undergo a debarking process before further processing. In the case of eucalyptus, debarking often occurs at the harvesting site. Chips from sawmills and other off-site sources typically do not have bark and can be directly used after screening. Debarked logs are then chipped to allow for efficient penetration of water, chemicals and heat. Maintaining a consistent chip size distribution is crucial for optimizing pulping processes and producing high-quality pulp.

In groundwood pulping, logs are used but in chemical and neutral sulfite semi-chemical pulping, thermomechanical pulping and chemi-thermomechanical pulping, chips are used. Kraft pulping, mechanical and thermomechanical pulping and groundwood processes rely on fresh wood to achieve a high-brightness pulp. In summer, when storing logs for mechanical pulping, it is common practice to moisten the woodpiles to prevent drying and darkening. This is especially crucial in sulfite pulping, where a controlled storage of chips encourages the gradual breakdown of extractives in the wood through oxidative and enzymatic processes, resulting in pulp with low extractive content.

3.5.3 Summary and prospect

The printing and publishing industry (PPI) is undergoing a landscape shift. Notably, there's a decline in output from North America and Europe, which has allowed Asia to surge to the forefront where it accounts for over 40 per cent of the world's PPI products. This decrease in demand can be attributed to the growth of other markets and the impact of digitalization. Forecasts suggest the Internet will increasingly supplant printed documents and traditional advertising methods. Consequently, companies worldwide are either scaling down production or exploring innovative market niches to create new high-value-added products. It is important to note, however, that this transition does not signify the disappearance of the PPI industry in the wake of digitalization. While the graphic paper sector may be contracting, the PPI sector as a whole is expanding, as other products like packaging and hygiene items step in to fill the gap left by the declining demand for graphic paper.

The paper industry has an important role in energy and the forests industry, and, therefore, the transition towards a bioeconomy. It touches on sociotechnical systems such as chemicals, biofuels for transport, bio-based materials, and agriculture. The demand for pulp and paper is subject to a range of factors that influence its trajectory. Factors influencing the market demand for paper and pulp are as follows:

Digitalization and electronic communication: The increasing prevalence of digital communication has been followed by a decline in the demand for certain types of paper products like newspapers, magazines, and traditional mail. This trend will likely continue, potentially reducing demand for certain paper products.

E-commerce and packaging: On the other hand, e-commerce has increased demand for packaging materials, including corrugated boxes and other paper-based packaging solutions. As online shopping grows, it is expected to sustain or even boost the demand for certain paper products.

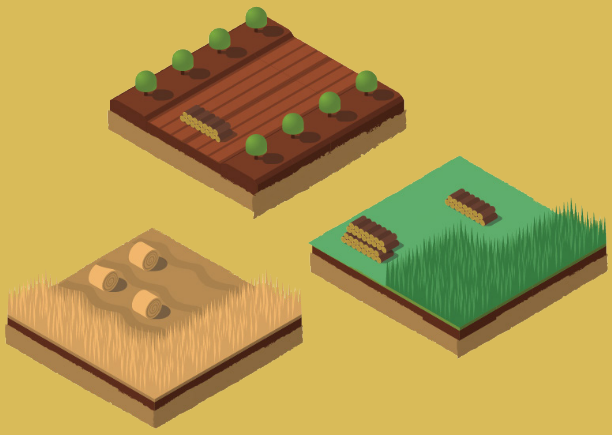
Sustainable practices and environmental concerns: There's a growing emphasis on sustainability in the paper industry. This includes increasing recycling rates, adopting sustainable forestry practices, and developing alternative fibre sources. These initiatives aim to mitigate the impact on natural resources.

Alternative fibre sources: Research and development efforts are under way to find alternative sources of fibre for paper production, such as agricultural residues, non-wood fibres and even algae. If successful, these innovations could reduce the reliance on traditional wood pulp.

Emerging markets and economic growth: The demand for paper products is often closely tied to economic growth. As emerging economies continue to develop, there may be an increase in the demand for paper and packaging products.

Such changes in pulp and paper demand will, in reverse, have an impact on natural resources. Wood pulp remains a primary source for paper production, and sustainable forestry practices and certification programmes are crucial to ensure that the demand for wood does not lead to deforestation or habitat degradation. A combination of technological advancements, sustainability efforts and evolving consumer preferences will likely shape the future of the pulp and paper industry. Balancing these factors will be crucial in minimizing the impact on natural resources.

4 Land use, biodiversity and bioeconomy



The bioeconomy significantly impacts global land use due to the rising demand for bio-based products and bioenergy. This demand leads to changes in land use, often involving the conversion of conventional agricultural land for bio-based feedstock production, potentially competing with food production and encroaching on natural ecosystems. In the bioeconomy, advanced technologies and genetically modified crops intensify agriculture, altering land-use dynamics by requiring more inputs and infrastructure. This high-intensity agriculture can strain land resources and ecosystem health. Expansion of the bioeconomy frequently results in deforestation and habitat loss, especially in regions with growing bio-based industries. Forested areas are cleared to make room for bio-based feedstock cultivation, destroying critical habitats and biodiversity.

Additionally, the bioeconomy's significant demand for water resources, particularly in water-intensive crops like sugar cane , adds pressure to land use through the allocation of land for irrigation infrastructure. These impacts underscore the importance of adopting sustainable practices, robust regulatory frameworks and careful land-use planning in the bioeconomy. These measures are crucial to ensure its growth is balanced with preserving vital ecosystems and resources.

4.1 Indispensable impacts of bioeconomy on global land use

The bioeconomy centres around the sustainable use of renewable biological resources like plants and microorganisms to create diverse products, services and energy. It spans sectors such as agriculture, textiles, chemicals and energy, offering solutions to global challenges like climate change, food security, energy independence and sustainability (Többen *et al*. 2022). However, it also has significant implications for land use.

The increasing demand for biomass creates competition between agriculture and forests for land use (Skarbøvik *et al*. 2020). The large-scale energy generation from biomass can lead to global land-use changes, causing environmental issues like carbon stock depletion, biodiversity loss, excessive nutrient usage and increased freshwater consumption (Immerzeel *et al*. 2023; Vermaat *et al*. 2023). It is vital to systematically assess these impacts for sustainable land use while pursuing bioeconomy goals.

4.1.1 Land is crucial to the global bioeconomy

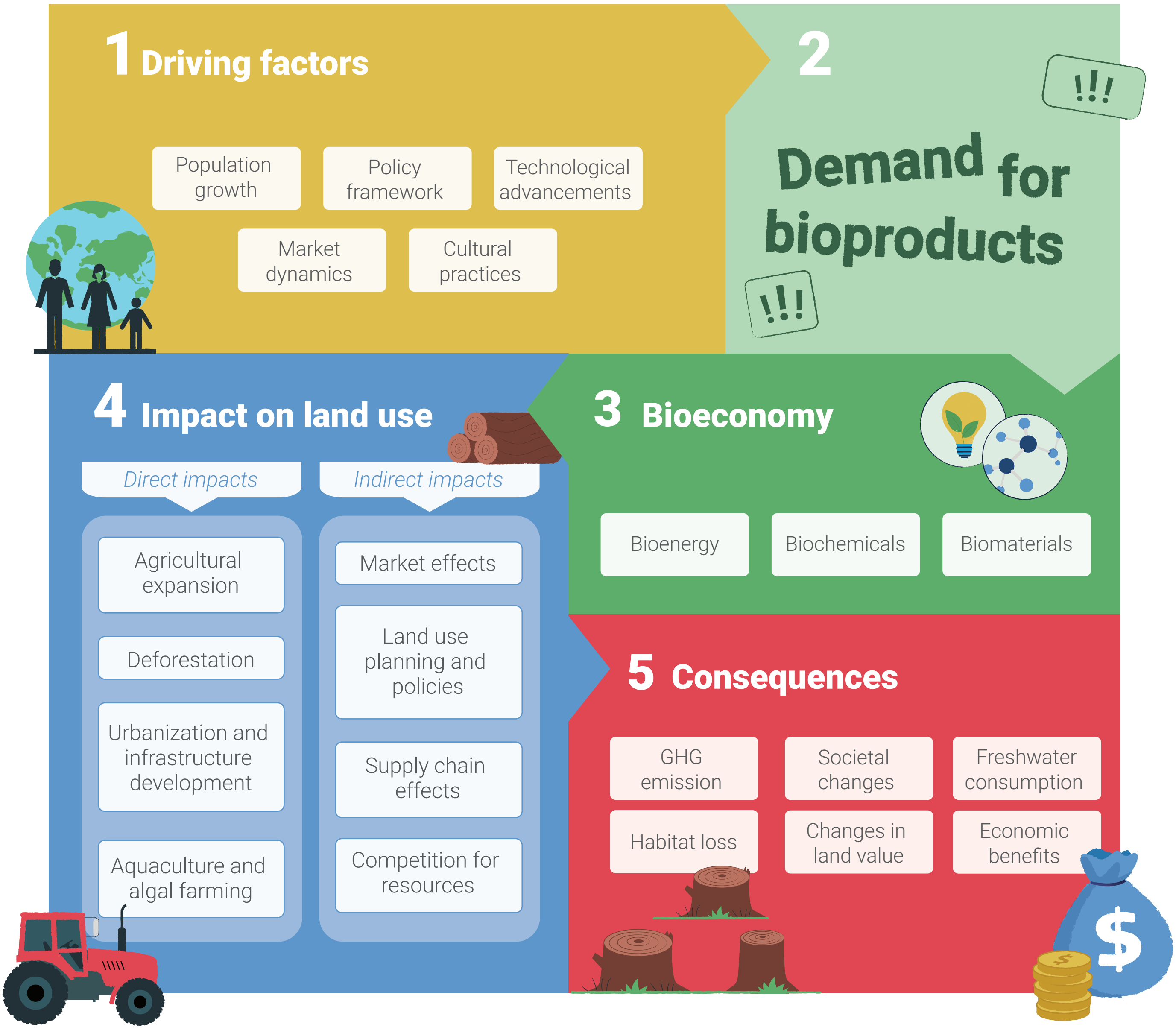
The land is crucial to the bioeconomy as it provides raw materials and energy carriers, from food to fuels, underlining its central role in sustaining life and industry (Többen *et al*. 2022). In addition, the land is also essential for maintaining ecosystem balance, providing services like carbon sequestration, water purification, climate regulation and biodiversity support (World Bank 2022).

The challenge arises from the finite nature of bio-productive land. Earth has limited land for agriculture, forestry, and other uses (Nabuurs *et al*. 2023). This land is vital for meeting food demands, producing renewable resources and supporting ecosystems. Human pressures on these lands are increasing due to population growth, urban expansion and resource extraction. As we pursue bioeconomy goals, understanding the land's finite and irreplaceable nature is crucial. Balancing sustainable development with preserving ecosystem services and biodiversity on limited land is a complex challenge. Responsible land management, conservation and innovative approaches are necessary for the bioeconomy to thrive without compromising our vital land resources (Immerzeel *et al*. 2023).

4.1.2 Impact mechanisms of bioeconomy on land use

The bioeconomy's impact mechanisms on global land use are complex and multifaceted. They encompass environmental, social, economic and policy-related factors that require careful consideration to ensure that the bioeconomy can contribute to sustainable development while minimizing adverse effects on land resources and ecosystems. The impacts of the bioeconomy on land use refer to how the production, consumption and trade of bio-based products and services influence land-use practices and patterns, both directly and indirectly, within the borders of a country.

Fig. 4.1 Impact mechanisms of bioeconomy on land use



1) Direct impacts of bioeconomy on land use

Direct impacts of the bioeconomy on land use, occurring within national boundaries, result from bioeconomy activities. These impacts are related to the production and consumption of bio-based products and services and can manifest at various stages in the supply chain, from raw material extraction to disposal.

Agricultural expansion: One significant direct impact is the expansion of agricultural land to grow biofuel crops, such as corn and sugar cane for bioethanol (Wang and Khanna 2023). This expansion can lead to land-use changes, including converting non-agricultural land into biofuel crop fields. For example, a country might increase the cultivation of sugar cane to meet the rising demand for bioethanol as an alternative fuel, leading to the conversion of non-agricultural land into sugar cane fields.

Deforestation: In the bioeconomy, forests are a significant source of biomass for products like wood pellets, paper and bioenergy (Barañano *et al*. 2022). For instance, clearing forests to establish eucalyptus plantations for paper production. Sustainable forest management practices are employed to extract biomass, which directly influence land use in forested areas (USA, Department of the Interior and Department of Agriculture n.d.).

Infrastructure development: Bioeconomy-related constructions, including biorefineries and processing plants, are established to convert biomass into value-added products. These industrial installations require land for construction and operations, contributing to changes in land-use patterns in specific regions (Holm-Nielsen and Ehimen 2014). For example, building biorefineries in rural areas to convert agricultural residues into bio-based chemicals affects land use in those regions.

Aquaculture and algal farming: Bioeconomy activities involving aquatic organisms, such as fish farming and algae cultivation, require the allocation of land and waterbodies for these purposes. This allocation directly impacts land use in coastal and aquatic environments (European Commission 2018b; Thomas *et al*. 2022).

2) Indirect impacts of bioeconomy on land use

Indirect impacts stemming from complex cause-and-effect relationships within the bioeconomy supply chain can lead to consequential effects on land use. These secondary effects, not immediately apparent and occurring at a distance from primary bioeconomy operations, can ripple through the supply chain and the broader economy, potentially prompting changes in land use.

Market effects: Increased demand for bio-based products can trigger competition for land between food and bio-based feedstock production, as it influences crop prices and land values (Strapasson *et al*. 2017). This dilemma of "food versus fuel" has gained substantial attention (Popp *et al*. 2014). Changes in domestic demand and supply can even impact land-use decisions in other regions (USA, Department of Agriculture Economic Research Service and Office of the Chief Economist 2011). For example, a heightened domestic demand for biofuels can raise prices for crops like corn or sugar cane, incentivizing farmers in different areas to convert additional land into biofuel feedstock production.

Supply chain effects: Bio-based product supply chains encompass various stages, from raw material production to distribution and consumption. While the cultivation stage directly impacts land use, various factors in this stage can indirectly affect land-use patterns, including feedstock type, cultivation location and production scale (García-Velásquez, Leduc and van der Meer 2022; Stellingwerf *et al*. 2022). Transporting feedstock, which typically has low energy density and values, from farms to processing facilities and manufacturing sites, plays a significant role. The choice of transportation modes and distances can indirectly influence land use through infrastructure development and land allocated to transportation routes (Bailey, Leong and Fitzgerald 2015). The location and size of processing facilities for converting feedstock into bio-based products also impact land use. These facilities may necessitate land for construction and operation. Decisions regarding site location, including proximity to feedstock sources and transportation infrastructure, can indirectly influence land-use choices (Solheim *et al*. 2023). End-of-life management practices for bio-based products, including disposal or recycling, can affect land use. The primary use of landfills for disposal has implications for land use, whereas sustainable practices like composting or recycling can reduce the land-use footprint (D'Adamo *et al*. 2020; Zaborowska and Bernat 2023).

Competition for resources: As the bioeconomy expands, the competition over vital resources like water, fertilizers and pesticides intensifies. In regions with limited resources, this competition indirectly influences land use by affecting resource availability for various land uses. For instance, an increase in water-intensive bioenergy crop cultivation may compete with water resources necessary for food crop irrigation, potentially impacting land use for both sectors (Vermaat *et al*. 2023).

Land-use planning and policies: Land-use planning and policies play a crucial role in shaping the spatial distribution of various activities in a region. Bioeconomy initiatives often trigger adjustments in these policies to accommodate and promote sustainable bio-based activities. Changes in land-use planning and policies within the framework of the bioeconomy are characterized by adjustments in zoning regulations, the introduction of incentives, support for research and development, consideration of environmental conservation measures, infrastructure development planning and active community engagement. Implementation of bioeconomy-related policies may indirectly influence land by promoting the use of land-based biomass to reach climate, energy or other economic targets (European Commission 2023).

3) Environmental consequences from intensive land use

The intensification of land use for bio-based purposes can lead to significant environmental consequences, including habitat loss, biodiversity decline, soil degradation, water pollution and increased pressure on water resources (Lamers *et al*. 2021). These consequences vary based on feedstock type, land-use intensity and location.

One of the most significant environmental consequences is habitat loss. When natural ecosystems such as forests, wetlands or grasslands are converted into agricultural land for bio-based feedstock cultivation, it can destroy the habitats of various plant and animal species. This can result in a decline in biodiversity and negatively impact local ecosystems (Otero *et al*. 2020; de Queiroz-Stein and Siegel 2023). Intensive land use for bio-based feedstock cultivation, particularly for crops like palm oil or soybeans, can also drive deforestation in tropical regions. Deforestation contributes to habitat loss and releases stored carbon into the atmosphere, contributing to climate change.

Intensive agricultural practices often require fertilizers and pesticides, which can run off into nearby waterbodies, polluting them. Additionally, excessive water use in intensive agriculture can exacerbate water scarcity issues, especially in regions with limited water resources (Mateo-Sagasta, Zadeh and Turral 2017).

Intensive land use can lead to soil degradation through erosion, compaction and nutrient depletion. This can reduce the long-term productivity of the land and result in reduced crop yields (Borrelli *et al*. 2017). Land-use change and converting natural ecosystems into agricultural land can release GHGs, primarily CO_2 and methane, into the atmosphere. Additionally, intensive agricultural practices can contribute to nitrous oxide emissions, another potent GHG (Galford *et al*. 2010; West *et al*. 2010).

As elucidated in the United Nations factsheet on women and climate change, the environmental consequences of land use can also affect women in different ways. As forests diminish, the availability of crucial resources diminishes concurrently, creating a scenario where women find themselves grappling with increased challenges in fulfilling their multifaceted roles. The depletion of resources presses women to invest more time and effort in meeting their daily needs, exacerbating the burdens they already bear (United Nations 2009). Consequently, it is important to recognize their roles, knowledge, and vulnerabilities in these contexts.

4.1.3 Bioeconomy poses negative impacts on global land: Case studies

Deforestation and palm oil expansion

The rapid growth of oil palm cultivation, initially from Africa but now widespread in South-East Asia, has seen substantial expansion globally, averaging 0.7 million hectares annually from 2008 to 2017. Palm oil, the primary product derived from oil palms, dominates the edible oil market in Africa and Asia, despite its controversial environmental and social impacts, particularly deforestation (Meijaard *et al*. 2020).

High-resolution satellite maps reveal that oil palm expansion in Indonesia and Malaysia, from 2001 to 2015, resulted in significant forest biomass loss, approximately 50.2 teragrams of carbon each year. Most expansions occurred through large-scale plantations, while small-scale plantations encroached on higher-density forests post-2007 (Xu *et al*. 2022). Remote sensing data indicates that oil palm plantations covered at least 19.5 million hectares globally in 2019, with South-East Asia accounting for 17.5 million hectares (Wagner, Wentz and Stuhlmacher 2022). Accounting for factors like young plantations and mixed-species, agroforests could expand this figure to 21.5–23.4 million hectares. Smallholders play a substantial role, ranging from 30 –60 per cent in parts of Malaysia and Indonesia to 94 per cent in Nigeria (Austin *et al*. 2015; Taheripour, Hertel and Ramankutty 2019).

The degree to which oil palm expansion replaces forests varies by region. Between 1972 and 2015, approximately 46 per cent of new plantations encroached on forests, while the remainder replaced different land uses (World Wildlife Fund 2024). Deforestation rates differ, with Malaysia at 68 per cent and the Peruvian Amazon at 44 per cent, while other regions show lower percentages (Ordway *et al*. 2019). Industrial plantation-driven deforestation in Indonesia and Malaysian Borneo has decreased since 2011, but smallholders may increase their plantings.

Amazon rainforest soya bean production

Brazil's Amazon, home to the world's largest remaining tropical forest, faces significant challenges resulting from soya bean production. Historically, cleared forest land in the Amazon was used mainly for cattle pasture. In the early 2000s, a shift occurred, with soya bean cultivation replacing cattle pasture, particularly in Mato Grosso. This transition turned the Amazon's soya bean production into a global industry, making Brazil the world's second-largest exporter. Soya bean expansion, particularly in Mato Grosso, has intensified, with double-cropping alongside crops like corn becoming common. This shift is driven by both soybean growers and cattle ranchers, often involving the purchase of land from ranchers who have previously cleared and grazed it, pushing deeper into the rainforest (Neill *et al*. 2013; Marin *et al*. 2022). The Amazon rainforest plays a vital role in maintaining global biodiversity, rainfall recycling, water supply for Brazilian agriculture, and carbon storage. Deforestation in the Amazon jeopardizes these functions and contributes to climate change by releasing stored carbon into the atmosphere.

Eliminating deforestation from the supply chains of firms exporting Brazilian soy to the EU or China from 2011 to 2016 could have reduced global deforestation by 2 per cent and Brazilian deforestation by 9 per cent. Therefore, requiring traders to eliminate deforestation from supply chains can significantly impact deforestation reduction (Villoria *et al*. 2022). To protect the Amazon, it is essential to curb soybean demand through measures such as stabilizing the global population and reducing meat consumption. Balancing supply and demand now involves reducing demand rather than solely expanding supply for food and energy.

4.2 Bioeconomy and biodiversity

The impacts of land use and land-use change determine the long-term biomass production capacity (Crenna, Sozzo and Sala 2018). To simultaneously meet the growing global populational demand for food and feed and the increasing demand for agriculture-based biofuels, it is necessary to expand agricultural production. This intensifies competition for natural resources between sectors such as agriculture and industry, damaging ecosystems (Reijnders 2006; Wiloso, Heijungs and de Snoo 2012). This affects functions such as water conservation, carbon sequestration and habitat preservation in the region, leading to severe biodiversity loss or even near-complete loss (Kruitwagen *et al*. 2021). The development of the bio-based economy is closely linked to biodiversity, and biodiversity plays a crucial role in the evolution of the bio-based economy.

4.2.1 Role of biodiversity in the bioeconomy

Biodiversity encompasses the full spectrum of life on Earth, including species, genes and ecosystems. The "Kunming-Montreal Global Biodiversity Framework", established at the fifteenth Conference of the Parties to the United Nations Convention on Biological Diversity, outlines the need for biodiversity conservation and sustainable use. It is indispensable for maintaining ecological equilibrium, with diverse species performing various functions within ecosystems (Cardinale 2012). Biodiversity offers diverse resources and ecosystem services, from food and raw materials to safeguarding water sources and regulating the climate. Various species within ecosystems play distinct roles, and their interactions are crucial for ecological balance. Diminishing biodiversity can lead to ecosystem collapse and ecological crises. Concurrently, biodiversity provides a wealth of resources for human society.

A multitude of species on Earth supplies humans with a wide array of food resources, including various crops, fruits and vegetables. Moreover, biodiversity provides diverse raw materials such as wood, fibres, rubber and resins with extensive construction, industry and manufacturing applications. For example, tropical rainforest timber is an essential resource for constructing furniture and building materials, while rubber trees in South-East Asian nations serve as raw materials for insulation and roofing. Biodiversity also supports numerous ecosystem services, including but not limited to protecting water sources, enhancing soil fertility, regulating the climate and mitigating natural disasters. These ecosystem services directly and indirectly affect human society's well-being and health.

With the ascent of the bio-based economy, biodiversity plays a pivotal role in ensuring sustainable development. The bio-based economy relies on biological resources such as plants, microorganisms and animals to produce biofuels, biomaterials and biopharmaceuticals. However, sustaining the bio-based economy hinges on the judicious management and preservation of these resources. Overexploitation and unsustainable practices can imperil biodiversity and, by extension, the bio-based economy's sustainability.

Mitigating the adverse impact of bioenergy production on biodiversity and ecosystems is paramount. Some regions have implemented certification requirements to safeguard high conservation value biodiversity habitats from harm during biofuel production. These requirements encompass biodiversity and ecosystem protection principles, encompassing GHG emissions, conservation, soil health, water quality and air pollution.

Comprehensive measures must be undertaken at both policy and practical levels to ensure the continued existence of biodiversity and its contribution to economic growth in the bio-based economy. Striking a balance between the demand for bio-based products and biodiversity conservation is indispensable for sustainable development, fostering a win-win situation that promotes economic growth while preserving our natural heritage.

4.2.2 Interplay between the bioeconomy and biodiversity

The intricate relationship between the bio-based economy and biodiversity is characterized by potential conflicts and opportunities. Key areas of concern include bioenergy, land use, and biodiversity conservation (Wise *et al*. 2009; Cardinale *et al*. 2012).

The goals of biodiversity conservation can sometimes limit the available land for biomass production, raising challenges in balancing these two factors (Kastner, Erb and Haberl 2015). It is imperative to comprehensively understand the risks and opportunities and implement appropriate policies to foster a harmonious and sustainable coexistence.

Challenges posed by the bio-based economy

As global energy demand surges, bioenergy stands out as a sustainable solution (OECD and FAO 2017). Biofuels and bioenergy hold promise in reducing carbon emissions and conserving habitats, yet their rising demand brings concerns. The pursuit of biomass can escalate land requirements and prices, potentially spurring the expansion of new agricultural areas. Such expansion may target “marginal” lands to avoid clashing with food crops, which can detrimentally affect natural ecosystems (Tilman *et al*. 2009; Gelfand *et al*. 2013). Even agricultural and forestry residues may have concealed costs since these residues play vital roles in soil fertility and biodiversity protection (Reijnders 2013; Victorsson and Jonsell 2013). Research worldwide underscores that replacing natural ecosystems with bioenergy crops, especially high-yield ones, can significantly harm biodiversity (Núñez-Regueiro, Siddiqui and Fletcher Jr. 2021).

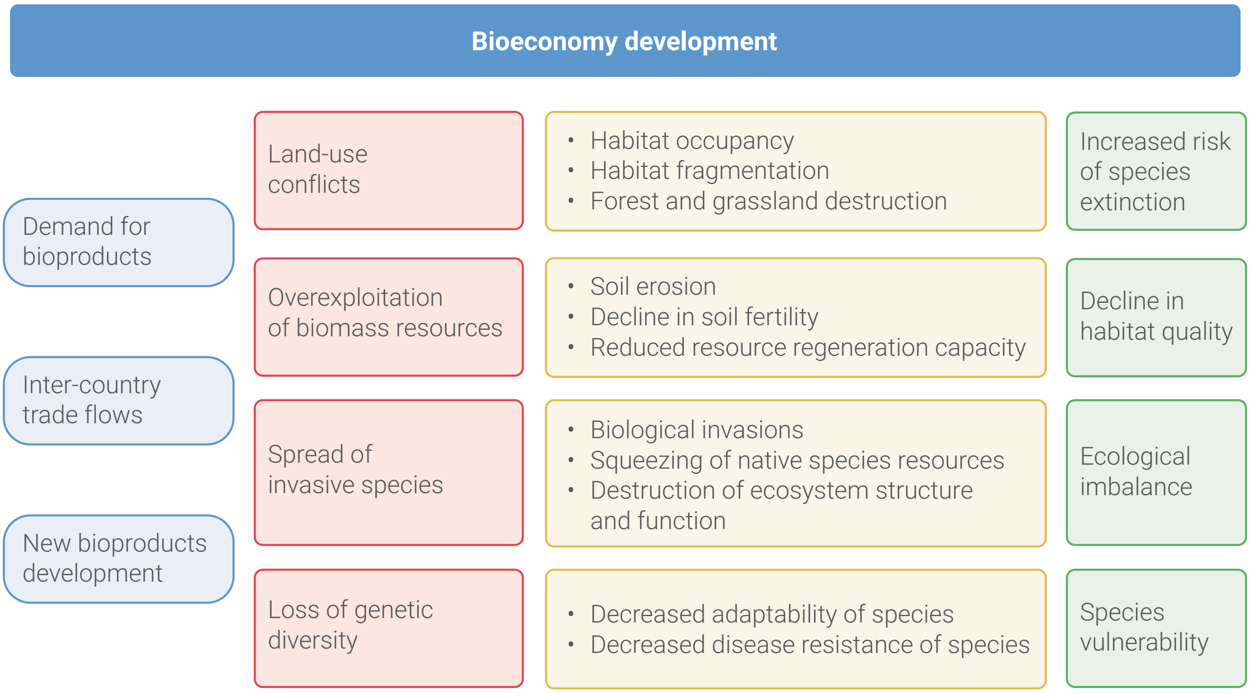
The intricate relationship between the bio-based economy and biodiversity involves multiple sectors, leading to habitat destruction, land-use conflicts and fragmentation of natural habitats. These factors can severely threaten various species, particularly those already at risk of extinction. Further, the overexploitation of biological resources and the transboundary movement of bio-based products can lead to the depletion of species and the introduction of invasive alien species. Additionally, excessive utilization of genetic resources can result in the loss of genetic diversity, compromising species’ adaptability and disease resistance.

International trade and transportation of bio-based products often involve the transboundary movement of large quantities of goods, potentially leading to the invasion of alien species. Further, in pursuit of bioenergy production, some regions introduce exotic energy crops such as energy maize, sugar cane and oil palm. These crops can grow rapidly in new ecosystems, encroaching upon the survival space of local flora and altering local ecological balances.

Developing new bio-based products may require the extensive utilization of genetic resources, such as the genetic resources of crops and livestock. Excessive or improper utilization of genetic resources can result in the loss of genetic diversity, affecting species’ adaptability and disease resistance.

The impact mechanisms of the bio-based economy on biodiversity encompass land-use conflicts, overexploitation of biological resources, the spread of invasive species and genetic diversity loss. To ensure sustainable bio-based economy development, measures must be taken to mitigate these adverse impacts, including thoughtful land-use planning, sustainable agricultural and forestry practices, invasive species control, eco-friendly pesticide use and adherence to international conservation policies.

Fig. 4.2 Impact mechanisms of bioeconomy on biodiversity



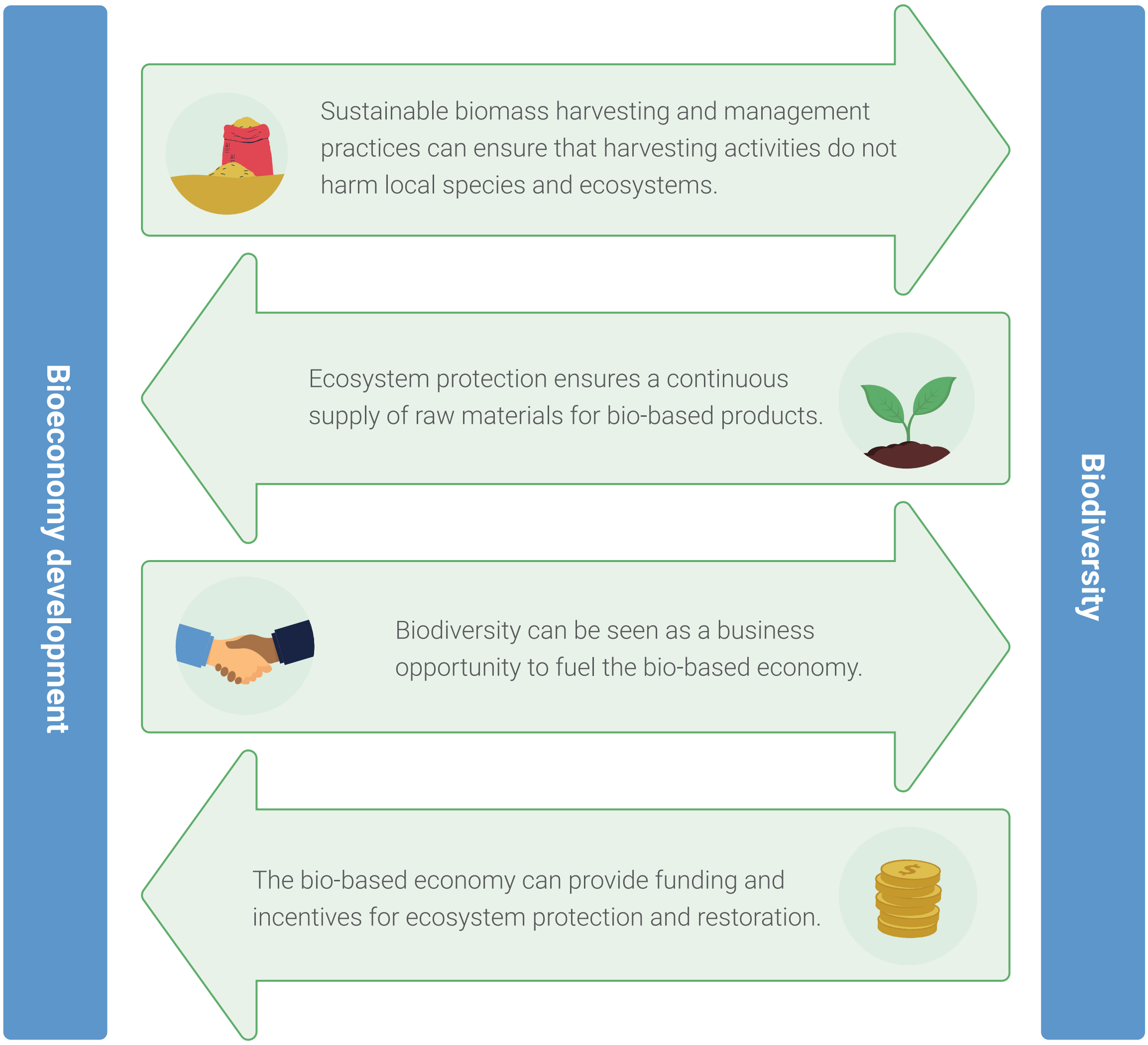
Synergies between the bio-based economy and biodiversity

The bio-based economy can coexist harmoniously with biodiversity by adopting sustainable harvesting and management practices. This approach seeks to ensure a continuous supply of resources without harming ecosystems and species, thereby preventing extinction and degradation. Biodiversity conservation and bio-based product production can mutually support one another, with sustainable methods ensuring that collection activities do not harm local species and ecosystems.

Moreover, biodiversity can present economic opportunities that support the bio-based economy. Developments in areas like ecotourism and biodiversity research can stimulate regional economic growth while driving bio-based product innovation. The bio-based economy has the potential to contribute to ecosystem conservation and restoration by supporting relevant projects and actively enhancing biodiversity.

This harmonious approach seeks a win-win scenario for economic growth and biodiversity conservation. To assess the relationship between the bio-based economy and biodiversity, the key is to ensure that bio-based economic development does not irrevocably harm biodiversity and instead aims to promote their coexistence and sustainability through sustainable practices, fostering the well-being of the bio-based economy and biodiversity conservation.

Fig. 4.3 Impact mechanisms of bioeconomy on biodiversity



Sustainable biomass harvesting and management practices can ensure that harvesting activities do not harm local species and ecosystems.

Ecosystem protection ensures a continuous supply of raw materials for bio-based products.

Biodiversity can be seen as a business opportunity to fuel the bio-based economy.

The bio-based economy can provide funding and incentives for ecosystem protection and restoration.

4.2.3 Typical regional bio-based product and biodiversity development cases

Oil palm plantation in South-East Asia

Achieving sustainable development hinges on striking a balance between the competing demands of agriculture (SDG 2) and biodiversity (SDG 15). This equilibrium is seen in the production of vegetable oils, particularly palm oil, and the trade-offs it entails. Predictions indicate that the global demand for vegetable oils will surge by 46 per cent by 2050, creating a complex web of consequences for biodiversity, food security, climate change, land degradation and livelihoods (Meijaard *et al*. 2020).

The cultivation of oil palm, a major contributor to the vegetable oil market, epitomizes these challenges. Palm oil's contentious nature arises from its profound environmental and social impacts and the opportunities it presents. Directly, oil palm development leads to the loss of natural habitats, a decline in woody biomass, and peatland drainage, culminating in reduced biodiversity, compromised water quality and increased GHG emissions (Laurance *et al*. 2012). The global demand for palm oil has led to the extensive replacement of vital forests, housing a wealth of biodiversity, with monoculture oil palm plantations in South-East Asia, tropical Africa and South America (Bergamo *et al*. 2022).

Tragically, most taxonomic groups in these plantations exhibit lower species diversity and abundance than natural forests. In Indonesia and Malaysia, 38 per cent and 68 per cent of oil palm plantations have supplanted forests, respectively. Since 1973, almost 16,000 square miles of tropical rainforest on the island of Borneo have been cleared for oil palm plantations, accounting for one fifth of the total forest clearance since 1973 and soaring to 47 per cent since 2000 (Rosner 2018). The rapid expansion of oil palm in India, increasing more than 30-fold since 1991, particularly in biodiversity-rich north-eastern regions, jeopardizes biodiversity and local livelihoods, potentially leading to the endangerment of globally threatened species and landscapes.

Sugar cane ethanol production in Brazil

Sugar cane ethanol production in Brazil is another illustrative case of the intricate relationship between biodiversity concerns and biofuel sustainability. While sugar cane cultivation boasts a long history in Brazil, the need to address sustainability and biodiversity conservation has gained prominence due to the desire to access international markets.

Biodiversity loss in Brazil primarily results from human activities, with habitat loss because of land-use changes being the leading driver (Powers and Jetz 2019). Expanding agricultural activities in biodiversity hotspots, such as the Atlantic Forest and Cerrado, introduce issues such as invasive species and excessive fertilizer use, exacerbating eutrophication and chemical contamination. The central-west region of Brazil, an agricultural frontier, has witnessed substantial sugar cane and crop cultivation expansion at the expense of conservation areas in the Cerrado. From 2000 to 2011, around 20 per cent of agricultural expansion was concentrated in this region, with Goiás becoming the second-largest sugar cane producer nationally.

Responding to concerns about forest loss and indirect sugar cane expansion impacts, the Brazilian Government implemented the sugar cane agro-ecological zoning policy. This initiative emphasizes the utilization of extensive pasturelands and grasslands, designating "exclusion zones" for sugar cane, such as the Amazon, current crop production areas, lands with unsuitable slopes for mechanical harvesting, and areas subject to regulations like the Forest Code. Government credit and support are restricted to planned expansion areas, while the economic zone allows sugar cane cultivation in regions that are naturally suitable for it, like the Cerrado.

In both the case of oil palm and sugar cane ethanol production, the balance between economic growth and biodiversity conservation requires thoughtful measures to prevent irreversible harm to ecosystems and species. Sustainable practices, like the ones mentioned above, enable a win-win scenario for the bio-based economy and biodiversity, nurturing their coexistence and sustainability.

4.3 Paving the way for a circular bioeconomy

Amid pressing environmental challenges, the transition to a bio-based economy has emerged as a global imperative. The journey from a fossil-fuelled past to a biomass-based future promises to address issues like food security, health, industrial restructuring and energy stability (Bugge, Hansen and Klitkou 2016). But the path to a bio-based economy must be paved with a deep consideration of the intricate relationship between biodiversity and the development of such an economy. Multifaceted, multi-approach strategies are essential to mitigating the negative impacts on biodiversity, fostering the sustainable evolution of the bio-based economy.

4.3.1 Optimizing land-use strategies

Numerous studies have illuminated the link between land-use changes and biodiversity loss in the journey towards a bioeconomy. The art of land-use management emerges as a pivotal aspect of ensuring sustainable development. In agriculture, enhancing productivity per unit area through methods like organic and intensive production is essential to reducing land requirements for food, fibre and bioenergy production while meeting the world's hunger needs (FAO 2011b; Donnison *et al*. 2021).

Leveraging biofuel processing by-products as animal feed in the livestock sector can offset conventional feed production's negative land-use effects (Berndes *et al*. 2015). As rising land prices and expanded employment opportunities bolster land management, wasteful land resource utilization can be mitigated (Kline *et al*. 2015).

However, deforestation, a great concern because of land conversion, directly threatens biodiversity (Lammertink 2004). Prudent forest management is essential, as it focuses on deforestation in productive sites with minimal biodiversity loss while preserving non-timber ecosystem services (Eyvindson, Repo and Mönkkönen 2018). Establishing mechanisms that compensate for ecological losses can protect forests (Castañé and Antón 2017).

Moreover, the intensification of agriculture, extensive forest management, and urbanization contribute to land degradation, compromising ecosystem resilience and indirectly causing ecological diversity loss (European Environment Agency 2015). Abandoned meadows and pastures also impact biodiversity loss as they are considered part of the overall biodiversity system (Scotti *et al*. 2020). Therefore, meticulous planning for food, fibre and bioenergy production and thorough environmental impact assessments are paramount. Preserving natural habitats from conversion is the primary measure for ensuring biodiversity protection (Calvin *et al*. 2021; Núñez-Regueiro *et al*. 2021). Implementing nature conservation measures near production areas can foster a symbiotic relationship between economic and ecological benefits, enhancing ecological cost-effectiveness in production processes (Müller-Lindenlauf, Deittert and Köpke 2010).

4.3.2 Diverse pathways to biodiversity conservation

In addition to land use, a plethora of pathways can be harnessed to reduce the direct and indirect loss of biodiversity during the bio-based economy's development. Prioritizing the reduction of harvesting levels is key to averting negative impacts on biodiversity (DiTommaso and Aarssen 1989). To this end, the judicious use of fertilizers, particularly inorganic fertilizers, is crucial in agricultural production to minimize biodiversity harm (Angerer *et al*. 2021).

Environmental heterogeneity, a global driver of landscape biodiversity, plays a pivotal role in biodiversity preservation (Eyvindson, Repo and Mönkkönen 2018). Promoting environmental heterogeneity by cultivating non-food bioenergy crops can offer substantial biodiversity benefits (Intergovernmental Panel on Climate Change 2019; Scotti *et al*. 2020). In forestry, policies should encourage the well-placed cultivation of bioenergy crops to boost environmental heterogeneity and landscape value (Werling *et al*. 2014). Foregoing centralized deforestation strategies is crucial as they lead to shorter rotation periods and greater ecological costs (Lassauce, Lieutier and Bouget 2012; Iordan, Verones and Cherubini 2018). To safeguard biodiversity, policy instruments can indirectly contribute by incentivizing additional planning and financial efforts for forest owners (Eyvindson, Repo and Mönkkönen 2018), thereby enhancing species diversity, resource flows, biomass supply and habitat sustainability.

4.3.3 Addressing regional disparities and equity issues in trade

Acknowledging differing levels of economic development among countries and regions, it is crucial to recognize their distinct roles and responsibilities in biodiversity loss. High-income countries and regions, especially the EU, contribute to biodiversity loss in less developed regions, particularly vulnerable tropical areas, through their international trade activities (Di Fulvio *et al*. 2019). For instance, the growing demand for food, particularly meat products, in high-income countries has led to extensive agricultural production expansion in lower-income countries, with hidden ecological costs (Koslowski *et al*. 2020).

The impact of trade further magnifies the disparity due to the fragility of natural habitats in these lower-income countries (Di Fulvio *et al*. 2019). Notably, biodiversity footprints tend to be higher in urban areas than rural ones, shaped partly by differences in economic development (Koslowski *et al*. 2020). Hence, alongside advocating for low-carbon diets, a reduced consumption of animal-based food and a curtailing of meat consumption, developed countries must balance fairness by enhancing legal frameworks, enforcing stringent sustainability criteria in trade processes and broadening the scope of responsibility to account for the biodiversity impacts of imported products (Calvin *et al*. 2021). In these efforts, it is vital to tailor management and policy measures to address regional disparities, varying developmental levels and diverse environmental conditions, ensuring optimal biodiversity conservation benefits.

4.3.4 Ecosystem services for a sustainable future

Ecosystem services, including biodiversity maintenance, confer substantial benefits to human life. These services can be positively or negatively influenced during the transition to a bio-based economy. Beyond their aesthetic value, the cultivation of non-food bioenergy crops offers habitats and cover for wildlife. However, producing food and energy crops, such as potatoes, poses soil erosion risks (van Evert *et al*. 2013). In contrast, non-food energy crops maintain soil organic carbon and aid in flood mitigation (Holland *et al*. 2015; Milner *et al*. 2016). To ensure a sustainable transition to a bioeconomy, it is essential to consider the impact of development on other ecosystem services and biodiversity. This comprehensive approach can facilitate economic and ecological conservation synergy, offering the conditions for sustainable bioeconomy development and human well-being.

5

Climate change mitigation potential, risk assessment and adaptation strategies for bioeconomy

5.1 The bioeconomy's contribution to climate change mitigation

The development of bioeconomy has multiple linkages with carbon flows (Fig. 5.1). The effect of bioeconomy on climate change mitigation is mainly reflected in four ways:

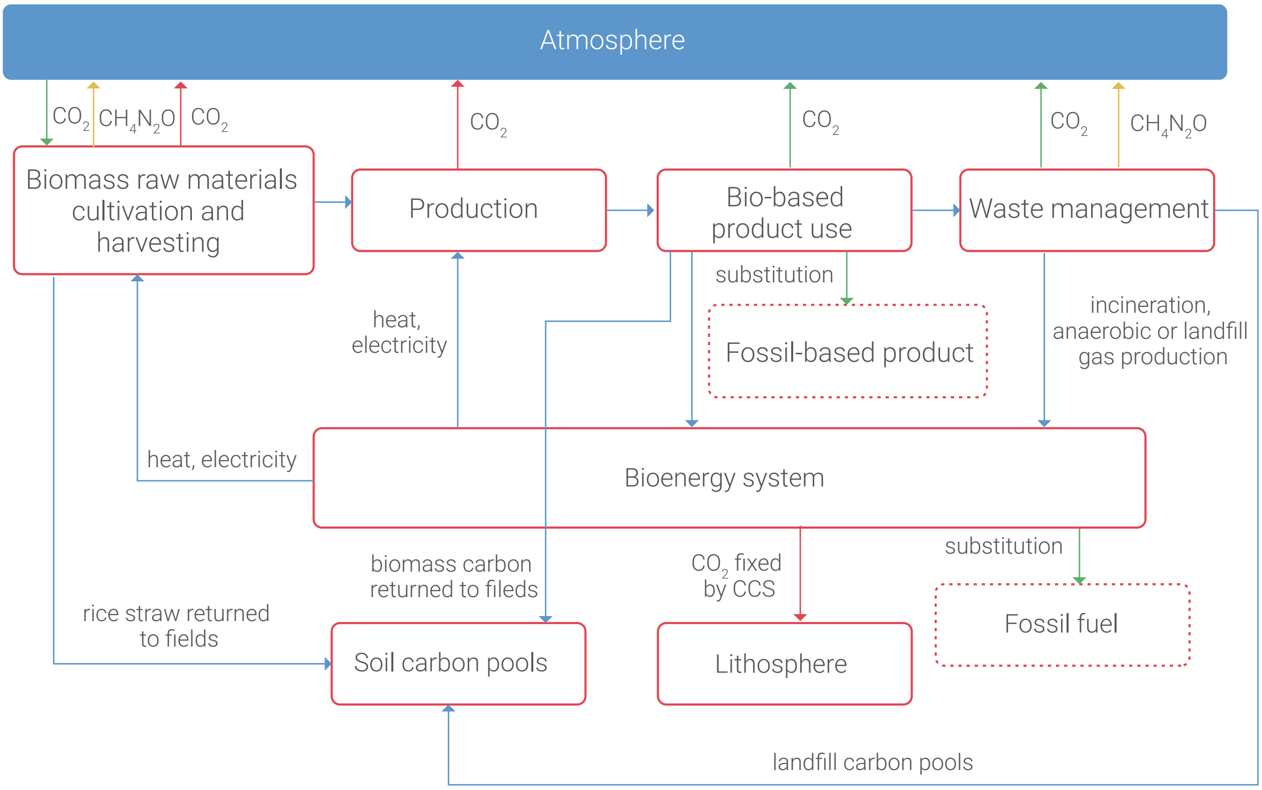
Carbon sinks from biomass. Plants absorb CO_2 from the atmosphere during their growth and convert it into organic matter. Traditional sink enhancement technologies in agroforestry mainly include afforestation, reforestation and forest management, conservation farming in agriculture, management of grasslands and wetlands, and coastal ecological projects (Yu *et al*. 2022).

Substitution of GHG-intensive products and fossil fuels. Substitution effects exist in all industries. Engineered wood can replace steel and cement (Smyth *et al*. 2017; Gustavsson *et al*. 2021), bioplastics can replace petroleum-based plastics (Brodin *et al*. 2017), and bioethanol and biodiesel can replace fossil fuels such as oil and natural gas.

Carbon storage for bio-based products. The use of bio-based products results in the transfer of carbon absorbed by biomass from the atmosphere to the carbon pool of bio-based products, and the duration of storage of this carbon in bio-based products ranges from a few years to a few hundred years, depending on the type of product, its end-use and function (Levasseur *et al*. 2013). The longer the carbon is stored, the more time is allowed for regrowing biomass to absorb an equivalent amount of carbon from the atmosphere (Mason, Yeh and Skog 2012).

Utilization of waste biomass resources. Biomass waste can be used to generate electricity, manufacture biofertilizer or produce biomass materials (Minowa, Kojima and Matsuoka 2005; Garedew 2018). Biomass waste is traditionally disposed of in landfills, open piles and incinerators, which produce not only large amounts of CO_2 but also methane and other gases that have a higher greenhouse effect. Therefore, converting it into bioenergy or valuable products not only saves resources, but also effectively reduces GHG emissions (Tripathi *et al*. 2019). According to the World Wildlife Fund, industrial biotechnology-based products and energy could reduce CO_2 emissions by 1 billion to 2.5 billion tons per year by 2030 (Bang *et al*. 2009). Of the four ways mentioned above, the emissions avoided by substitution are artificially defined, whereas the other three actually occur. This subsection describes the applications of bio feedstock in the construction, industrial and energy sectors.

Fig. 5.1 Carbon flow, removals and emissions in the atmosphere, biomass, and bio-based products systems



5.1.1 Biomaterials in construction

In the construction sector, some biomaterials (such as wood and hemp) can be used in their raw state, while others (such as mycelium and food scraps) can be fused with other materials and then transformed into useful composites. Wood is the most widely used and oldest renewable material in construction due to its good availability, renewability, workability and high strength-to-weight ratio. In addition to wood, agricultural and fishery wastes such as straw, biomass ash and discarded shells can also be applied to the preparation of concrete, which not only achieves the resourceful utilization of wastes, but also effectively improves the properties of concrete.

These biomass feedstocks and products avoid significant emissions by replacing GHG-intensive materials used in construction, such as steel and cement. In addition, because wood buildings have lifetimes of decades or even centuries, biomass carbon can be stored in them for long periods.
In the short term, the regeneration of the forests after harvesting can reabsorb carbon from the atmosphere. This delayed emission can have a significant climate-cooling effect in the short term. However, bio-based products for buildings may have negative impact on GHG emission reduction, such as the significant fossil carbon emissions generated from the production, biogenic methane emissions from end-of-life disposal, and the reduced carbon sink of forests caused by timber harvest. Therefore, assessing the climate benefits of bio-based products for construction requires a systemic perspective that takes into account all emissions and sinks.

The climate benefits of engineered wood products for construction are widely recognized. On the one hand, the GHG intensity of wood is significantly lower than that of steel and concrete in terms of the life cycle carbon emissions. Hart, D'Amico and Pomponi (2021) compared various building structural systems such as steel, concrete and engineered timber frames and found that concrete frames and steel frames have much higher mass and whole life embodied carbon emissions than timber frames. Robati and Oldfield (2022) analysed the life cycle embodied carbon of timber and concrete buildings in Australia, finding that large timber-framed buildings typically have lower embodied carbon, with an average of approximately 417 kg CO_2-e/m², but are also subject to the lifetimes of building products, allocation of biogenic carbon emissions and other uncertainties. On the other hand, wood-based panels, stress laminated timber and mass timber have significant GHG reduction potential in terms of the climate impacts of the large-scale use of engineered wood products. Many studies have assessed the climate impacts of engineered wood products used in construction, and almost all of them found that wood used in construction can produce GHG emission reductions or even harmful emissions. Wang *et al*. (2022) quantified the climate impacts of the wood-based panels industry in China using a dynamic life cycle assessment approach and found that, over the time frame of the study, the wood-based panels industry can achieve carbon neutrality. Mishra *et al*. (2022) state that the transition to wood-based cities could reduce emissions by 106 gigatons of CO_2 by 2100. Thus, in conclusion, bio-based products in the construction sector can fulfil a significant GHG reduction potential and form an important pathway towards carbon neutrality in the construction sector.

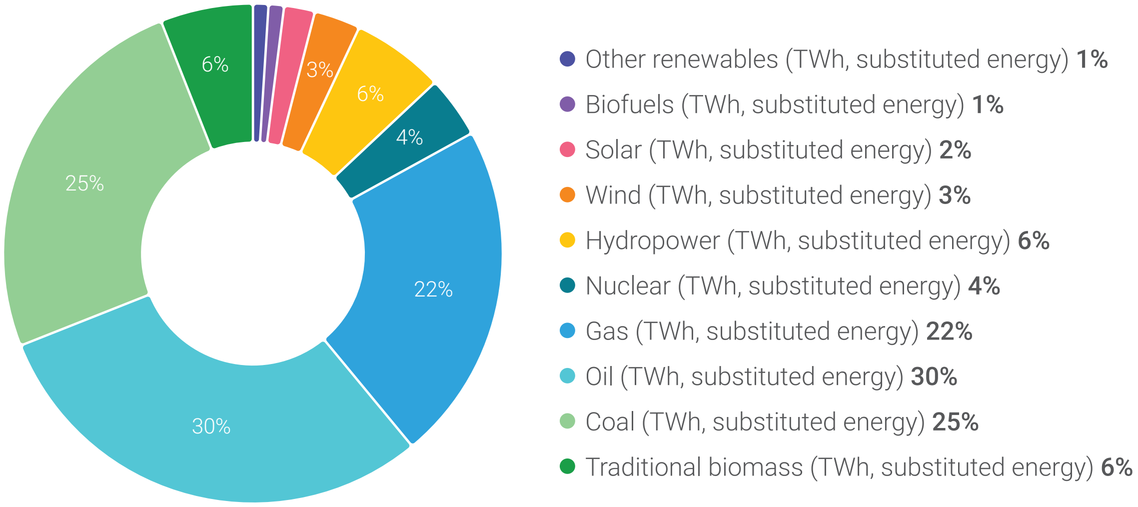
5.1.2 Bio-based industrial feedstock

Bio-based materials, produced from renewable raw materials such as grains, straw, bamboo and wood powder (Diao *et al*. 2016), have the characteristics of renewability, low-carbon intensity and biodegradability and are expected to gradually replace traditional petroleum-based materials in some applications, which is an important direction for the development of the international new materials industry. Bio-based industrial materials mainly include the following categories: bio-based chemicals, bio-based plastics and bio-based fibres.

Plastics (Mittal, Mittal and Aggarwal 2022), rubber (Roy, Debnath and Potivaraj 2020), fibres (Yang, Wu *et al*. 2021; Hurmekoski *et al*. 2022) and many bulk traditional petrochemicals (Hakeem *et al*. 2023) are increasingly being replaced by industrial bioproducts from renewable feedstocks. Traditional chemical industry processes are characterized by high temperatures, high pressures and high levels of pollution, and the use of green resources such as biomass for the production of liquid fuels and chemicals creates opportunities for sustainable development in the chemical industry (Huang *et al*. 2021). The plastics industry currently consumes 8 per cent of the world's oil and accounts for about 4.5 per cent of total global carbon emissions from its production and use (Cabernard *et al*. 2022). Textiles can be classified into natural and chemical fibres, but natural fibres are limited, and to meet demand, petroleum fibres such as polyester, nylon and spandex have to be obtained from oil (Felgueiras *et al*. 2021). However, the high energy consumption of petroleum fibres in the production process makes the textile industry the second most polluting industry in the world after the oil industry.

The climate mitigation benefits of bio-based chemicals are clear, given that chemicals are currently produced globally from oil, gas and coal, which are resource- and energy-intensive and polluting. Winter, Meys and Bardow (2021) performed a prospective life cycle assessment of bio-based aniline production and compared it with fossil-based aniline production, noting that the cradle-to-grave global warming impacts can be reduced by 35–69 per cent. Forte *et al*. (2016) conducted a life cycle assessment of the environmental performance of bio-based 1,4-butanediol produced by the direct fermentation of wheat, straw and sugar and determined that the environmental impacts of bio-based 1,4-butanediol are generally lower compared with fossil-based 1,4-butanediol. Plastics are the bulk material with the strongest growth in global production, and the bio-based plastics industry can achieve negative emissions in the long term through carbon sequestration in bio-based plastic products and in landfills (Stegmann *et al*. 2022). Bio-based fibres are widely used in the textile industry as an alternative to chemical fibres. Bio-based fibres are derived from plant-based fibres that absorb carbon from the atmosphere through photosynthesis and store it in the plant, which is then stored in fibre products such as textiles and can be used as a substitute for fossil-based products. Through this carbon storage and delayed emission effect, bio-based fibres have a positive climate change impact in terms of reducing atmospheric GHG emissions (Liu *et al*. 2023).

Fig. 5.2 Global primary energy consumption structure in 2022



Note: TWh stands for terrawatt hour.

5.1.3 Bioenergy

A promising renewable energy source, bioenergy has become the fourth-largest energy source after coal, oil and natural gas, with great potential for development (Fig. 5.2). Many countries have established clear biomass energy development goals and formulated appropriate plans, regulations and policies to promote bioenergy development. Bioenergy generates climate benefits primarily through the substitution of fossil fuels. There are no carbon storage benefits because of its short life span for bioenergy. The source of biomass used for bioenergy also affects its climate benefits, and it is reasonable to assume the raw material as a carbon-neutral feedstock if it is derived from biomass with a short rotation period, such as energy crops and crop waste. However, if the raw material is derived from biomass with a rotation period of decades or even hundreds of years, such as from forests, the long time required for forest regeneration results in a time lag between bioenergy emissions and reabsorption, which may make it challenging to observe emission reduction benefits on shorter time scales.

Industry-level climate impact assessments have shown that the climate impacts of bioenergy are not always positive and that many uncertain factors, such as biomass sources, types of alternatives, temporal boundaries and management practices, affect its climate benefits (Dwivedi, Khanna and Fuller 2019). Almost all bioenergy that uses agricultural residues as feedstock sources has GHG emission reduction benefits. Residues can be considered by-products or waste, so emissions from feedstock collection can be excluded from being attributed to bioenergy carbon footprint as a result of the short rotation period of agriculture production. However, there is a great deal of uncertainty for bioenergy using logs or forest residues as feedstock (Schulze *et al*. 2012; Zanchi, Pena and Bird 2012). In the short-to-medium term, the use of roundwood for bioenergy will instead increase emissions in the atmosphere (Buchholz, Gunn and Sharma 2021), and achieving GHG emission reductions is possible if good forest management practices are applied, but this will take hundreds of years (McKechnie *et al*. 2011; Garvie, Roxburgh and Ximenes 2021). The type of alternative fuel is also an important factor in the climate benefits of bioenergy (Nielsen, Nord-Larsen and Bentsen 2021). Generally, bioenergy substitutes for fossil fuels with high-carbon intensity, such as coal and diesel, have large GHG emission reductions, while substitutes for fuels with low-carbon intensity, such as natural gas and hydroelectric power generation, have small emission reductions or even increase emissions. Therefore, the climate impacts of bioenergy use are not always positive. To fully realize its benefits, we need to make efforts in feedstock selection, technology pathways and the range of alternatives.

5.1.4 Summary and prospect

Overall, the bioeconomy has significant climate mitigation potential, but this potential varies from sector to sector. The climate benefits of using engineered wood products for construction are significant, and emerging bio-based materials such as bio-based chemicals, bio-based plastics and bio-based fibres carry great potential to replace fossil-based materials in the future. For bioenergy, however, the climate benefits are controversial and related to uncertainties in feedstock types, technology choices, types of substitutes, time boundaries, management practices and other factors.

While the bioeconomy can generate climate benefits through carbon storage and substitution, biomass also generates land-use change emissions and production emissions. For forest-based products, the higher the substitution efficiency, the more GHG emissions are avoided but the lower the forest carbon stock is; so, there is a need for trade-off between forest carbon sinks and harvested wood products carbon pools. Therefore, assessing the climate impact of the bioeconomy needs to use a systematic approach, weighing the dynamics of carbon across the components of the system. In addition, most current studies often ignore the constraints of biomass feedstock availability. Therefore, there is an urgent need for industry-wide climate impact assessments of bio-based products and bioenergy, taking into account the potential for biomass feedstock extraction, competition for raw materials and other constraints, to plan for the development of the bioeconomy more scientifically.

5.2 Climate risks on sustainable supply chains of biomass resources

5.2.1 Impact of climate risk on the supply of biomass resources

This part introduces the impacts of climate-related factors on the availability of biomass resources, including sudden-event impacts and slow-onset impacts from extreme events and chronic changes. Impacts arise from extreme events (e.g. hurricanes, droughts, heat waves) and chronic climate change (e.g. sea-level rise, desertification, glacial retreat, land degradation, ocean acidification, salinization) (Fig. 5.3). These changes may lead to changes in biomass resources regarding production, resource availability, trade and more, resulting in negative or positive effects.

Sudden-event impacts are so named for their suddenness, as well as the unforeseen events triggered by climate change such as extreme weather events (e.g. tropical cyclones, floods, droughts, and wildfires) (Raymond *et al*. 2020). Such impacts tend to dramatically impact biomass agriculture, forestry, fisheries and more in a short period. Slow-onset impacts are long-term, progressively visible changes triggered by climate change. The United Nations Framework Convention on Climate Change provides for eight slow-onset events: increasing temperatures, sea-level rise, salinization, ocean acidification, glacial retreat, land degradation, desertification and biodiversity loss (van der Geest and van den Berg 2021). These impacts will gradually accumulate over relatively long time scales, with persistent and progressive effects on the supply of biomass resources for agriculture, forestry and fisheries.

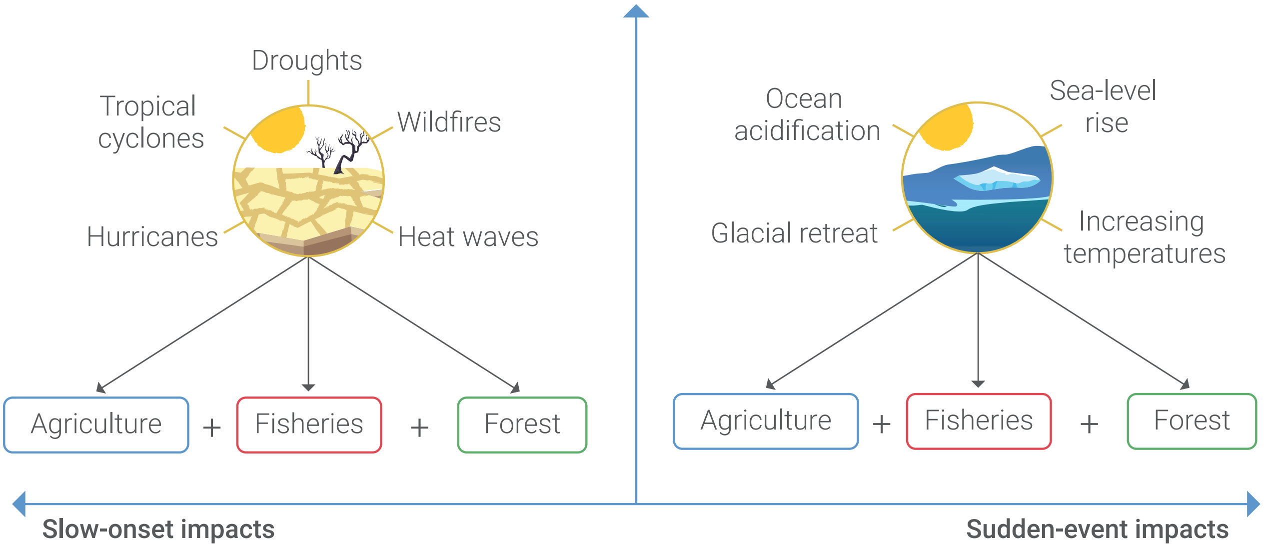
Typical examples of sudden-event impacts and slow-onset impacts will be selected in this section to discuss the ways and adverse consequences of climate risks on agriculture, fisheries and forestry.

1) Sudden-event impacts of climate risk on the supply of biomass resources

Heavy rainfall and flooding

The heavy rainfall and flooding triggered by hurricanes or typhoons pose a dual threat to crop growth and agricultural operations. In 2020, the number of malnourished individuals reached a staggering 811 million. Climate change, extreme weather events, conflicts, economic slowdown and recession, further exacerbated by the COVID-19 pandemic, are the primary driving force behind food insecurity, malnutrition and poverty (FAO 2021). The agricultural sector's vulnerability to climate change has been well substantiated in the literature. Shifts in temperature and precipitation patterns are anticipated to alter land and water regimes, consequently impacting agricultural productivity (Kurukulasuriya and Rosenthal 2003).

Fig. 5.3 Sudden and slow events caused by climate change



Floods have various impacts on agricultural production and productivity. First, crops washed away by floods result in significant losses. In many cases, crops cannot recover after floods and become contaminated. In regions prone to frequent flash floods or river floods, livestock can be lost or displaced, including fish in ponds with unstable waterbodies or structures. Pastures for livestock are also washed away. As well, heavy rainfall can have a significant impact on agricultural operations. The onset of flooding can lead to serious land erosion problems, as farmland and a large amount of soil are washed away, causing significant damage to otherwise fertile land. In addition, agricultural infrastructure, such as irrigation systems, canals and farm buildings, may also suffer damage during floods, further exacerbating the plight of biomass resource availability.

Heavy rainfall and flood storms can have multiple impacts on fisheries that can directly or indirectly affect the sustainability of fishing and the ecological health of fishery resources. Changes in precipitation patterns lead to shifts in the quantity and timing of run-off from storms and snowmelt into waterbodies. This has resulted in heightened soil erosion risks and increased pollutant export in watersheds (Qiu *et al*. 2021). These events alter water ecosystems, disrupting habitats for fish and aquatic organisms and resulting in reduced fishery resources.

For forestry, exposure to extreme rainfall triggers flooding and inundation, affecting forest growth. The relationship between climate change and forest pests and diseases is intricate. Climate change is anticipated to result in more frequent and severe outbreaks of forest pests and diseases, posing a substantial threat to forest health (Grünig *et al*. 2020). High temperatures and drought conditions are conducive to the proliferation of certain pests and diseases, which may lead to a decline in forest health.

Drought

Persistent high temperatures may lead to faster water evaporation from crops, increasing transpiration, leading to soil drought and limiting water and nutrient uptake by the plant root system. In addition, drought may make crops vulnerable to pests and diseases, further impairing yield and quality. Drought strains water supplies and makes it difficult for irrigation systems to provide sufficient water to farmland. Lack of water for crops can lead to stunted growth and ultimately affect the yield and quality of biomass resources.

For fisheries, during droughts, the water level of waterbodies can drop significantly, reducing the size of lakes, rivers and other waterbodies, which in turn can reduce the habitat for fish and decrease the conditions for their reproduction and growth. At the same time, water quality may deteriorate due to water bodies' scarcity, affecting fishery resources' ecological health. Because of water scarcity, water temperature tends to increase, directly affecting some fish species' survival and reproduction.

For forestry, drought leads to a reduction in soil moisture, which directly affects tree growth. Droughts can cause vegetation to wither and soil to dry out, making forests susceptible to forest fires. Forest fires can be highly damaging to forest ecosystems and resources and affect forest resources that can be used for biomass energy and timber, for example. Drought conditions can lead to a decline in the health of some trees, making them more susceptible to pests and diseases.

2) Slow-onset impacts of climate risk on the supply of biomass resources

Impacts of climate risk on the availability of biomass resources for agriculture

Climate change will profoundly impact critical food production sectors, and it is anticipated that industries, including agriculture and fisheries in tropical regions, will suffer losses (Cinner *et al*. 2022). One significant effect of climate change on agricultural climate resources is evident in the altered precipitation patterns resulting from global warming, which affects the supply of irrigation water resources and consequently impacts crop growth. Rising temperatures may lead to shifts in planting seasons, affecting the growth cycles of specific crops. It is projected that by 2100, due to climate change, tropical regions may lose up to 200 suitable plant growth days per year (Mora *et al*. 2015). Climate warming may also lead to an expanded range of certain pests and diseases, causing more harm to crops. Increased temperatures could result in changes in soil moisture and quality, potentially adversely affecting the growth and yield of specific crops.

Impacts of climate risk on the availability of biomass resources for fisheries

The environmental changes caused by the rising concentration of atmospheric GHGs have brought about diverse climate hazards to the productivity of marine and freshwater systems and the availability of aquatic feed resources and subsequent production processes (Dzwonkowski *et al*. 2020). With the increase in global temperatures, ocean temperatures are also continuously rising, exerting a significant impact on the distribution of fisheries resources and ecological balance. As temperatures rise, some tropical fish species may migrate north for more suitable habitats. This may lead to formerly abundant resources in certain regions becoming scarce, potentially requiring upper-level fisheries to adapt to changes in species distribution (Pörtner *et al*. eds. 2022). Deep-sea organisms are less affected by temperature changes, but if the temperature changes too dramatically or rapidly, it may disrupt deep-sea ecosystems. Given that the warming extent over large landmasses exceeds that of the oceans, it is anticipated that some nations' freshwater fisheries will face "very high" levels of hazard by the mid-twenty-first century, particularly in water-scarce regions such as North Africa and the Middle East (Dzwonkowski *et al*. 2020).

Impacts of climate risk on the supply of forest biomass resources

Global warming and extreme weather events impact forest growth and health. Increased temperatures and changes in precipitation are causing forests in some areas to face drought and water stress, affecting trees' average growth and survival. Climate change leads to increased global temperatures and altered precipitation patterns, directly affecting forest growth cycles. Warmer and drier climatic conditions may lead to slow growth of forest trees in some areas, resulting in drought and water stress for trees.

5.2.2 Biomass supply chain and climate risk transmission

1) The landscape of the global biomass supply chain

As a renewable resource, biomass is driven by economic development and energy demand, leading to a growing trend in its trade. Biomass trade is primarily concentrated between developed countries and emerging economies. There is a significant cross-regional movement of various forms of biomass, including raw biomass flows, processed biomass flows or biomass flows within products, all serving multiple end uses, as depicted in Fig. 5.4. Due to the complexity of trade, climate risks may be transmitted along supply chains.

2) The climate risks of the bioeconomy

Expanding climate risks: Expanding economic activities can potentially result in irreversible environmental damage at both local and global levels. For example, climate risks such as the greenhouse effect (Paltsev 2001) can be amplified along the biomass resource supply chain. Some developing countries have not yet committed to reducing GHG emissions, and unilateral emission reduction efforts by industrialized nations may transfer unchecked emissions to these regions. This phenomenon of emissions shifting is referred to as "carbon leakage". Therefore, the development of the biomass economy may exacerbate carbon leakage, thereby expanding climate risks, manifesting in several ways:

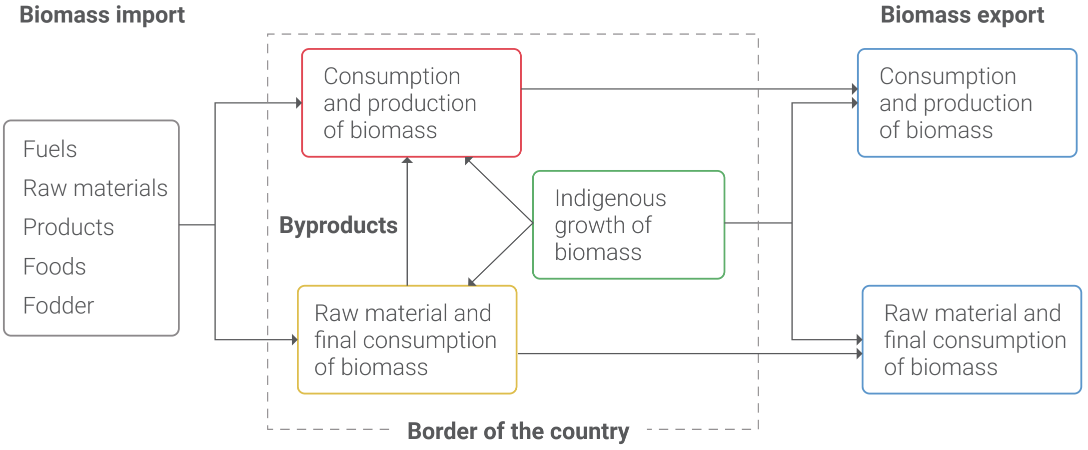
a. In terms of energy: Changes in international fossil fuel trade. Carbon reduction policies may trigger direct or indirect impacts through international trade. Commitments to biomass from carbon reduction countries may increase, leading to a reduced demand for fossil fuels, resulting in lower fossil fuel prices and an increased demand for and emissions from fossil fuels in developing countries.

b. In product markets or competition: Changes in international trade of goods and services reflect carbon emissions generated during production. For instance, in recent years, the EU has seen a significant increase in the import of biofuels to meet the demand in the transportation sector. During this period, the import of biodiesel increased sevenfold between 2005 and 2008, primarily from Malaysia and Indonesia (palm oil) (Di Lucia, Ahlgren and Ericsson 2012). Consequently, changes in land use in countries exporting palm oil may lead to global carbon leakage (Don *et al*. 2012).

c. Regarding technology and policy diffusion: International spillover effects. Because of changing carbon reduction requirements in carbon reduction countries and the competitiveness of energy-intensive industries, these countries may vigorously develop their local biomass economies and transfer energy-intensive industries to other regions. This may lead to an increase in climate risks in the regions receiving these transfers.

Research indicates that the regions causing the largest induced carbon leakage are the EU (36–51 per cent), the USA (28–34 per cent) and Japan (13–18 per cent) (Paltsev 2001). These regions exhibit significant variations in the ratio of induced leakage to their emission reductions. These results are influenced by global trade patterns. Energy-intensive industries may be redistributed to non-reducing regions through foreign direct investments.

Fig. 5.4 Illustration of biomass flows within and between countries



Source: Heinimö and Junginger (2009).

Therefore, reducing carbon leakage mitigates climate risks and achieves climate goals.

Mitigating climate risks: High transportation costs and trade redundancy mitigate climate risks.

Bilateral trade characteristics significantly influence the extent of carbon leakage: high transportation costs hinder industrial relocation and reduce carbon leakage. High transportation costs can reduce the possibility of cross-border biomass industry migration, thus lowering the risk of carbon leakage. Biomass companies tend to implement emission reduction measures in their current locations, such as adopting cleaner production technologies. While high transportation costs can reduce the global migration of the biomass industry, in some cases, it may lead to the transfer of carbon emissions between regions.

On the other hand, increasing trade redundancy can promote the resilience of supply chains and trade systems and reduce the impact of climate risks. Firstly, diversification in trade makes the system more resilient, allowing it to better cope with extreme climate events and reduce climate risks. If a region's biomass supply is disrupted due to climate events, the system can still rely on other sources to meet demand, thus mitigating potential supply bottlenecks. Additionally, trade redundancy can also reduce the economic impact of climate risks. When redundancy exists in the supply chain, even in the face of climate-related risks, it can alleviate the pressure of price increases and supply shortages. This benefits consumers and businesses as it helps maintain stable prices and availability.

5.3 Climate risk mitigation and adaptation strategies for bio-based economy

5.3.1 Ways to improve the bioeconomy's mitigation potential in response to climate change

Carbon sink management: In forestry, we need to implement sustainable forest management practices, including harvesting methods, forest health management, selection of tree species and forest regeneration after deforestation. In agriculture, we need to improve agricultural management practices, including the use of fine farming techniques, land conservation measures, waste recycling and ensuring the sustainable management of farmland. Implementing sustainable carbon sink management is essential not only to ensure that agroforestry biomass continues to absorb CO_2 from the atmosphere but also to provide biomass resources for the bioeconomy in the long term.

Technological innovation and efficiency improvement: In biomass pretreatment, there is a need to develop efficient and cost-effective biomass pretreatment technologies for converting biomass into a feedstock that can be used for energy, chemicals and materials production. Regarding catalytic conversion of biomass, we should upgrade biomass-catalysed conversion technologies, including biomass-to-liquid fuel, biomass-to-bio-based chemicals and biomass-to-bio-natural gas conversion. The most important is to facilitate the transition of these technologies from the laboratory to market-scale utilization.

Increased efficiency of product use: At the downstream, which means the product end of the bioeconomy, we can extend biomass carbon storage by increasing the service of long-life products, replacing higher carbon-intensive materials to avoid more fossil carbon emissions and refining the spatial allocation of fossil fuel use to take into account the mix of fuels used locally to maximize the substitution benefits of bioenergy. Disposal of bio-based products at the end of their life is also very important, and we can minimize GHG emissions to the atmosphere by recycling biomass resources, energy recovery from combustion, and methane capture from landfill.

5.3.2 Mitigating the impact of the biomass economy on climate risks

Strengthening preparedness for increasing frequency or prolonged duration of extreme events like droughts and high temperatures is the most direct measure to address the impacts of climate change. This approach can directly avoid high costs and reduce the severe damage to expensive, long-term

investments and infrastructure (Kurukulasuriya and Rosenthal 2013). Additionally, enhancing adaptability is considered a crucial component in responding to the impacts of climate change on agriculture, forestry, fisheries and aquaculture. Many studies emphasize the need for adaptive measures in addition to mitigation strategies. The Intergovernmental Panel on Climate Change notes that achieving adaptability through adjustments in processes, practices or structures is a key method for mitigating potential adverse effects of climate change and enhancing favourable impacts (McCarthy *et al*. 2001).
One example of climate-smart agriculture in the agricultural sector involves adopting climate-adaptive crop varieties as part of a national agricultural transformation strategy to mitigate frequent disasters and shocks. For instance, adopting climate-adaptive peanut varieties has increased agricultural production, consumption and smallholder commercialization in West Africa (Tabe-Ojong *et al*. 2023).

Ensuring a diverse biomass resource supply chain and establishing a relevant risk assessment system are paramount. This encompasses the need for diversification in the biomass resource supply chain to mitigate the risk of resource scarcity caused by climate change while also considering the sustainability of biomass resources, including their regenerative capacity, land-use changes and ecosystem impacts. Further, the risk assessment system for the biomass resource supply chain must account for vulnerable nodes and potential bottlenecks in the supply chain, effectively addressing risks stemming from natural disasters, climate change and policy shifts. Moreover, implementing appropriate management strategies for the biomass resource supply chain can enhance the accuracy of predicting biomass resource availability, ultimately promoting a more sustainable biomass trade (Welfle *et al*. 2014). In summary, a diversified biomass resource supply chain, a risk assessment system, and effective management strategies collectively provide crucial support for achieving global carbon reduction goals, ensuring the sustainability and stability of the biomass resource supply chain, and contributing to the reduction of climate change risks.

6 Conclusions and recommendations

The bioeconomy, rooted in research, development and applications within the life sciences and biotechnology, is built upon biotechnological products and industries that aim to reduce reliance on fossil fuels for energy and industrial materials. This burgeoning field has gained increasing attention from academia, government and industries globally. But despite this growing interest, a precise, scientifically unified definition of the bioeconomy remains elusive. Still, countries have continued their efforts in promoting the bioeconomy.

6.1 Policy in promoting bioeconomy

Different regions worldwide have implemented policies to promote the bioeconomy, with the EU leading the way in developing national strategies. The EU's core objective is to adapt to a changing policy environment that aligns with the circular economy, Paris Climate Agreement and 2030 Agenda for Sustainable Development. Germany was the first to publish a national bioeconomy research strategy in 2010, followed by a policy strategy in 2013, while other European countries have focused on green or blue growth strategies and the circular economy.

Some Asia-Pacific emerging economies are highly innovative in the bioeconomy, focusing on high-tech and industrial innovation. Countries like Japan and Thailand have specialized bioeconomy strategies, while others prioritize biotechnology. Bioeconomy innovation is crucial for health-care sector improvements. Large economies such as China's and India's see biotechnology as a competitive area to innovate quickly. Bioenergy is important for India, Indonesia and New Zealand.

The African continent, with its rich biomass resources, has great potential for bio-based economic development. Bioeconomy initiatives are growing rapidly, with South Africa releasing a bioeconomy strategy in 2013 and the East African Macro-Regional Bioeconomy Strategy in 2020: seven East African countries have collaborated to develop a regional innovation-driven bioeconomy strategy, supported by the East African Innovation Network for the Development of Bioresources, to boost technology transfer and business development.

In recent years, the bioeconomy has gained political importance in Latin America and the Caribbean, with countries like Argentina, Brazil and Colombia developing strategies, although progress has been slow. Costa Rica published the region's first dedicated national strategy in August 2020. In North America, the USA has a comprehensive bioeconomy strategy emphasizing biotechnology and biomedicine, while Canada's industry-driven strategy focuses on agricultural biomass.

In addition to policies in different regions, emerging trends in global bioeconomy policies are also evolving, which is currently undergoing significant policy developments across four key dimensions: life cycle carbon disclosure policies, trade policies, digital transformation policies, and carbon pricing and carbon credits policies. These evolving trends are instrumental in shaping the future of the bio-based products sector. The bioeconomy affects local livelihoods in Brazil and Indonesia through crops like palm oil and soybean. While it can bring income and employment, excessive development can lead to environmental and social problems. Considering local livelihoods and supporting women's entrepreneurship is crucial for sustainable bioeconomy development. A holistic and gender-responsive approach to policy development, practices and implementation is important to ensuring bioeconomy activities contribute to sustainable livelihoods, women's empowerment and resilient communities, echoing Targets 22 and 23 of the Global Biodiversity Framework.

6.2 Bioresources and bioproducts production

The development of the bioeconomy relies on three generations of biomass resources, with challenges facing each generation. The future focus will be on advancing technology to fully utilize the second- and third-generation resources while considering potential food security issues. Biomass resource utilization methods can be divided into five categories: energy, raw material, feed, base material and fertilizer. The products with complicated conversion processes are included in the report, including bio-based energy, bio-based chemicals, bio-based plastics, textiles and pulp products.

Bio-jet fuels, specifically HEFA-SPK, are being analysed for commercialization in the aviation industry. Large-scale production plants require significant investment and face challenges with feedstock availability, economic viability and sustainability. Policy support and technological advancements are necessary to make bio-jet fuels competitive with traditional fuels in the market.

Bio-based platform compounds are increasingly produced from lignocellulosic feedstocks rather than starch-based materials, reducing competition for resources and contributing to food security. Waste biomass is an economical feedstock, and biotechnology reduces production costs. Genetic engineering and synthetic biology improve synthesis pathways, resulting in fewer by-products and more precise compound production, making commercial production more viable. This approach also reduces pollution and harnesses waste resources, promoting sustainability.

Bioplastics are a promising alternative to traditional plastics because of resource shortages and environmental impact. Cost-effectiveness and applicability are limiting factors, but cheap and abundant raw materials can help reduce production costs. Technical advances have improved the performance of bio-based plastics, making them viable alternatives. Regulatory incentives and increased production capacity, especially in Asia, are expected to drive bioplastic demand.

Natural fibres in textiles are preferred for their biodegradability and renewability, but they can negatively impact land and water resources during planting. Organic cotton cultivation and sustainable farmland management are effective solutions. The industry faces challenges like price-cost squeezes, and innovation and policy support are necessary for sustainable development. Emerging fibres like bamboo and wood fibre offer sustainable options for the textile fibre market.

The paper industry plays a crucial role in the transition towards a bioeconomy. Digitalization and e-commerce are affecting demand for certain paper products, with a decline in some areas and growth in others. Sustainability and environmental concerns drive efforts to increase recycling and adopt alternative fibre sources. Emerging markets and economic growth will also impact paper demand.

6.3 Enhancing sustainable land use and protecting biodiversity

The bioeconomy, driven by the sustainable use of biological resources, impacts global land-use patterns, leading to changes in agriculture, deforestation and habitat degradation, in turn affecting ecosystems and biodiversity. Balancing growth and resource conservation requires sustainable practices, regulatory frameworks and careful land-use planning.

The bioeconomy's connection to biodiversity requires balancing the latter's protection with economic growth. Policies and practices must address bioenergy land-use conflicts, resource overexploitation, invasive species and genetic diversity erosion. Sustainability efforts include land planning, sustainable practices, invasive species control, environmentally friendly pesticides and international conservation policies. The bioeconomy's high demand for water and land resources emphasizes the need for sustainable practices, strong regulations and careful planning to ensure balanced growth and conservation of ecosystems.

To achieve sustainable development of the bio-based economy, legal frameworks and responsibility boundaries should be enhanced and adapted to local contexts to augment conservation benefits. Emphasis should also be placed on accentuating other ecosystem services, promoting synergistic development between the economy and ecological preservation.

6.4 Interaction between bioeconomy and climate risk

Bio-based products and bioenergy have climate mitigation benefits, but their impact varies across regions and industries. Engineered wood products in construction and bio-based materials, chemicals and fibres can potentially lower carbon emissions. However, bioenergy's climate impact is controversial and biofuels should not be considered carbon-neutral. Improving the climate benefits of bio-based products involves increasing long-lived bioproducts, substituting carbon-intensive materials and utilizing waste biomass.

Climate change can cause extreme events, e.g. floods and droughts, which affect agriculture, forestry and fisheries in the bioeconomy. These events can damage infrastructure, reduce resource availability and increase pest and disease risks. Slow-onset impacts like changing precipitation patterns and rising temperatures also affect crop growth and fish distribution. Recognizing and addressing these impacts is crucial for sustainable bioresource management. Tackling the climate change needs carbon emissions reduction systematic coordination of various production and economic sectors as well as consumers' behaviour change. Women, particularly in developing countries, are often disproportionately affected by climate change, so designing bioeconomy strategies with a focus on gender can lead to resilient, equitable and socially sustainable outcomes. However, as much as women are disproportionately impacted, they can also be part of addressing and solving the climate change crisis.

7 References

Angerer, V., Sabia, E., von Borstel, U.K. and Gauly, M. (2021). Environmental and biodiversity effects of different beef production systems. *Journal of Environmental Management* 289, 112523. https://doi.org/10.1016/j.jenvman.2021.112523.

Atlas Big (2019). World Silk Production by Country. Atlas Big. https://www.atlasbig.com/en-us/countries-by-silk-production#. Accessed 24 January 2024.

Austin, K.G., Kasibhatla, P.S., Urban, D.L., Stolle, F. and Vincent, J. (2015). Reconciling oil palm expansion and climate change mitigation in Kalimantan, Indonesia. *PLOS One* 10(5), e0127963. https://doi.org/10.1371/journal.pone.0127963.

Bailey, A., Leong, G.J. and Fitzgerald, N. (2015). *Bioproducts to Enable Biofuels Workshop Summary Report*. United States: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. https://doi.org/10.2172/1252134.

Bang, J.K., Foller, A. and Buttazzoni, M. (2009). Industrial biotechnology: more than green fuel in a dirty economy? Exploring the transformational potential of industrial biotechnology on the way to a green economy. Industrial biotechnology: more than green fuel in a dirty economy? Exploring the transformational potential of industrial biotechnology on the way to a green economy, 22. https://www.cabdirect.org/cabdirect/abstract/20103110161.

Barañano, L., Unamunzaga, O., Garbisu, N., Araujo, A. and Garbisu, C. (2022). Towards the implementation of forest-based bioeconomy in the Basque Country. *EFB Bioeconomy Journal* 2, 100040. https://doi.org/10.1016/j.bioeco.2022.100040.

Baydar, G., Ciliz, N. and Mammadov, A. (2015). Life cycle assessment of cotton textile products in Turkey. *Resources, Conservation and Recycling* 104(A), 213-223. https://doi.org/10.1016/j.resconrec.2015.08.007.

Bergamo, D., Zerbini, O., Pinho, P. and Moutinho, P. (2022). The Amazon bioeconomy: Beyond the use of forest products. *Ecological Economics* 199, 107448. https://doi.org/10.1016/j.ecolecon.2022.107448.

Bergmann, J.C., Tupinambá, D.D., Costa, O.Y.A., Almeida, J.R.M., Barreto, C.C. and Quirino, B.F. (2013). Biodiesel production in Brazil and alternative biomass feedstocks. *Renewable and Sustainable Energy Reviews* 21, 411-420. https://doi.org/10.1016/j.rser.2012.12.058.

Berndes, G., Ahlgren, S., Börjesson, P. and Cowie, A.L. (2015). Bioenergy and Land Use Change–State of the Art. (2015). In *Advances in Bioenergy: The Sustainability Challenge*. Lund, P.D., Byrne, J., Berndes, P. and Vasalos, I.A. (eds.). West Sussex: John Wiley & Sons, Ltd. Chapter 16. 249-271. https://doi.org/10.1002/9781118957844.ch16.

Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C. *et al*. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications* 8(1), 2013. https://doi.org/10.1038/s41467-017-02142-7.

Bourdon, M., Lyczakowski, J.J., Cresswell, R., Amsbury, S., Vilaplana, F., Le Guen, M.-J. *et al*. (2023). Ectopic callose deposition into woody biomass modulates the nano-architecture of macrofibrils. *Nature Plants* 9(9), 1530-1546. https://doi.org/10.1038/s41477-023-01459-0.

Bozell, J.J. and Petersen, G.R. (2010). Technology development for the production of biobased products from biorefinery carbohydrates–the US Department of Energy's "Top 10" revisited. *Green Chemistry* 12(4), 539-554. https://doi.org/10.1039/B922014C.

Bracco, S., Calicioglu, O., Gomez San Juan, M. and Flammini, A. (2018). Assessing the contribution of bioeconomy to the total economy: A review of national frameworks. *Sustainability* 10(6), 1698. https://doi.org/10.3390/su10061698.

Brodin, M., Vallejos, M., Opedal, M.T., Area, M.C. and Chinga-Carrasco, G. (2017). Lignocellulosics as sustainable resources for production of bioplastics – A review. *Journal of Cleaner Production* 162, 646-664. https://doi.org/10.1016/j.jclepro.2017.05.209.

Buchholz, T., Gunn, J.S. and Sharma, B. (2021). When biomass electricity demand prompts thinnings in Southern US pine plantations: A forest sector greenhouse gas emissions case study. *Frontiers in Forests and Global Change* 4, 642569. https://doi.org/10.3389/ffgc.2021.642569.

Bugge, M.M., Hansen, T. and Klitkou, A. (2016). What is the bioeconomy? A review of the literature. *Sustainability* 8(7), 691. https://doi.org/10.3390/su8070691.

Cabernard, L., Pfister, S., Oberschelp, C. and Hellweg, S. (2022). Growing environmental footprint of plastics driven by coal combustion. *Nature Sustainability* 5(2), 139-148. https://doi.org/10.1038/s41893-021-00807-2.

Calvin, K., Cowie, A., Berndes, G., Arneth, A., Cherubini, F., Portugal-Pereira, J. *et al*. (2021). Bioenergy for climate change mitigation: Scale and sustainability. *GCB Bioenergy* 13(9), 1346-1371. https://doi.org/10.1111/gcbb.12863.

Calvo-Serrano, R., Guo, M., Pozo, C., Galán-Martín, Á and Guillén-Gosálbez, G. (2019). Biomass conversion into fuels, chemicals, or electricity? A network-based life cycle optimization approach applied to the European Union. *ACS Sustainable Chemistry & Engineering* 7(12), 10570-10582. https://doi.org/10.1021/acssuschemeng.9b01115.

Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P. *et al*. (2012). Biodiversity loss and its impact on humanity. *Nature* 486(7401), 59-67. https://doi.org/10.1038/nature11148.

Cascione, V., Roberts, M., Allen, S., Dams, B., Maskell, D., Shea, A. *et al*. (2022). Integration of life cycle assessments (LCA) in circular bio-based wall panel design. *Journal of Cleaner Production* 344, 130938. https://doi.org/10.1016/j.jclepro.2022.130938.

Castañé, S. and Antón, A. (2017). Assessment of the nutritional quality and environmental impact of two food diets: A Mediterranean and a vegan diet. *Journal of Cleaner Production* 167, 929-937. https://doi.org/10.1016/j.jclepro.2017.04.121.

China, Ministry of Industry and Information Technology, Development and Reform Commission, Ministry of Finance, Ministry of Ecology and Environment, Ministry of Agriculture and Rural Affairs, State Administration for Market Regulation (2023). Notice from the Ministry of Industry and Information Technology and six other departments on issuing a three-year action plan to accelerate the innovative development of non-food bio-based materials, 9 January. https://www.gov.cn/zhengce/zhengceku/2023-01/14/content_5736864.htm. Accessed 11 January 2024.

China, National Development and Reform Commission, Ministry of Industry and Information Technology, Ministry of Finance, National Forestry and Grassland Administration (2023). Notice of the National Development and Reform Commission and other departments on the issuance of the "Three-year Action Plan to Accelerate the Development of "Replacing Plastic with Bamboo"", 12 October. https://www.gov.cn/zhengce/zhengceku/202311/content_6913316.htm. Accessed 11 January 2024.

Chrisendo, D., Siregar, H. and Qaim, M. (2021). Oil palm and structural transformation of agriculture in Indonesia. *Agricultural Economics* 52(5), 849-862. https://doi.org/10.1111/agec.12658.

Chong, J.W.R., Khoo, K.S., Yew, G.Y., Leong, W.H., Lim, J.W., Lam, M. K. *et al*. (2021). Advances in production of bioplastics by microalgae using food waste hydrolysate and wastewater: A review. *Bioresource Technology* 342, 125947. https://doi.org/10.1016/j.biortech.2021.125947.

Chong, J.W.R., Tan, X., Khoo, K.S., Ng, H.S., Jonglertjunya, W., Yew, G.Y. *et al*. (2022). Microalgae-based bioplastics: Future solution towards mitigation of plastic wastes. Environmental Research 206, 112620. https://doi.org/10.1016/j.envres.2021.112620.

Cinner, J.E., Caldwell, I.R., Thiault, L., Ben, J., Blanchard, J.L., Coll, M. *et al*. (2022). Potential impacts of climate change on agriculture and fisheries production in 72 tropical coastal communities. *Nature Communications* 13(1), 3530. https://doi.org/10.1038/s41467-022-30991-4.

Costa Rica (2020). *National Bioeconomy Strategy: Costa Rica 2020–2030*. https://thedocs.worldbank.org/en/doc/de734572ac8e6b503423b40811d096c1-0350012021/related/The-Costa-Rica-Bioeconomy-Strategy.pdf.

Costa Rica, Ministry of the Environment and Energy, Ministry of Agriculture and Livestock. (2008). *Costa Rica National Programme on Biofuels (Programa Nacional de Biocombustibles) 2008*. San José. www.iea.org/policies/6255-costa-rica-national-programme-on-biofuels-programa-nacional-de-biocombustibles-2008.

Crenna, E., Sozzo, S. and Sala, S. (2018). Natural biotic resources in LCA: Towards an impact assessment model for sustainable supply chain management. *Journal of Cleaner Production* 172, 3669-3684. https://doi.org/10.1016/j.jclepro.2017.07.208.

da Silva César, A., de Azedias Almeida, F., de Souza, R.P., Silva, G.C. and Atabani, A.E. (2015). The prospects of using *Acrocomia aculeata (macaúba)* a non-edible biodiesel feedstock in Brazil. *Renewable and Sustainable Energy Reviews* 49, 1213-1220. https://doi.org/10.1016/j.rser.2015.04.125.

D'Adamo, I., Falcone, P.M., Imbert, E. and Morone, P. (2020). A socio-economic indicator for EoL strategies for bio-based products. *Ecological Economics* 178, 106794. https://doi.org/10.1016/j.ecolecon.2020.106794.

Das, P. and Gundimeda, H. (2022). Is biofuel expansion in developing countries reasonable? A review of empirical evidence of food and land use impacts. *Journal of Cleaner Production* 372, 133501. https://doi.org/10.1016/j.jclepro.2022.133501.

De Oliveira, F.C. and Coelho, S.T. (2017). History, evolution, and environmental impact of biodiesel in Brazil: A review. *Renewable and Sustainable Energy Reviews* 75, 168-179. https://doi.org/10.1016/j.rser.2016.10.060.

de Queiroz-Stein, G. and Siegel, K.M. (2023). Possibilities for mainstreaming biodiversity? Two perspectives on the concept of bioeconomy. *Earth System Governance* 17, 100181. https://doi.org/10.1016/j.esg.2023.100181.

Dessie, W., Xin, F., Zhang, W., Zhou, J., Wu, H., Ma, J. *et al*. (2019). Inhibitory effects of lignocellulose pretreatment degradation products (hydroxymethylfurfural and furfural) on succinic acid producing *Actinobacillus succinogenes. Biochemical Engineering Journal* 150, 107263. https://doi.org/10.1016/j.bej.2019.107263.

Di Fulvio, F., Forsell, N., Korosuo, A., Obersteiner, M. and Hellweg, S. (2019). Spatially explicit LCA analysis of biodiversity losses due to different bioenergy policies in the European Union. *Science of The Total Environment* 651(1), 1505-1516. https://doi.org/10.1016/j.scitotenv.2018.08.419.

Di Lucia, L., Ahlgren, S. and Ericsson, K. (2012). The dilemma of indirect land-use changes in EU biofuel policy – An empirical study of policy-making in the context of scientific uncertainty. *Environmental Science & Policy* 16, 9-19. https://doi.org/10.1016/j.envsci.2011.11.004.

Diao, X., Weng, Y., Huang, Z., Yang, N., Wang, X., Zhang, M. and Jin, Y. (2016) Current status of bio-based materials industry in China. *Chinese Journal of Biotechnology* 32(6), 715–725. http://journals.im.ac.cn/html/cjbcn/2016/6/gc16060715.htm.

DiTommaso, A. and Aarssen, L.W. (1989). Resource manipulations in natural vegetation: A review. *Vegetatio* 84(1), 9-29. https://doi.org/10.1007/bf00054662.

Don, A., Osborne, B., Hastings, A., Skiba, U., Carter, M.S., Drewer, J. *et al*. (2012). Land-use change to bioenergy production in Europe: Implications for the greenhouse gas balance and soil carbon. *GCB Bioenergy* 4(4), 372-391. https://doi.org/10.1111/j.1757-1707.2011.01116.x.

Donnison, C., Holland, R.A., Harris, Z.M., Eigenbrod, F. and Taylor, G. (2021). Land-use change from food to energy: Meta-analysis unravels effects of bioenergy on biodiversity and cultural ecosystem services. *Environmental Research Letters* 16(11), 113005. https://doi.org/10.1088/1748-9326/ac22be.

Dwivedi, P., Khanna, M. and Fuller, M. (2019). Is wood pellet-based electricity less carbon-intensive than coal-based electricity? It depends on perspectives, baselines, feedstocks, and forest management practices. *Environmental Research Letters* 14(2), 024006. https://doi.org/10.1088/1748-9326/aaf937.

Dzwonkowski, B., Coogan, J., Fournier, S., Lockridge, G., Park, K. and Lee, T. (2020). Compounding impact of severe weather events fuels marine heatwave in the coastal ocean. *Nature Communications* 11(1), 4623. https://doi.org/10.1038/s41467-020-18339-2.

Eastwood, C., Turner, J.A., Romera, A., Selbie, D., Henwood, R., Espig, M. *et al*. (2023). A review of multi-scale barriers to transitioning from digital agriculture to a digital bioeconomy. *CABI Reviews* 2023. https://doi.org/10.1079/cabireviews.2023.0002.

Embrapa (2020). Soja em números (safra 2019/20). https://www.embrapa.br/soja/cultivos/soja1/dados-economicos. Accessed 11 January 2024.

Enriquez, J. (1998). Genomics and the world's economy. *Science* 281(5379), 925-926. https://doi.org/10.1126/science.281.5379.925.

Euler, M., Krishna, V., Schwarze, S., Siregar, H. and Qaim, M. (2017). Oil palm adoption, household welfare, and nutrition among smallholder farmers in Indonesia. *World Development* 93, 219-235. https://doi.org/10.1016/j.worlddev.2016.12.019.

European Commission (2012). *Innovating for Sustainable Growth: A Bioeconomy for Europe*. Luxembourg: Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/1f0d8515-8dc0-4435-ba53-9570e47dbd51.

European Commission (2018a). *The Bioeconomy: Targeted Scenario n°2 – Glimpses of the Future from the BOHEMIA Study*. Luxembourg: Publications Office of the European Union. https://data.europa.eu/doi/10.2777/14047.

European Commission (2018b). *A Sustainable Bioeconomy for Europe: Strengthening the Connection Between Economy, Society and the Environment*. Luxembourg: Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/edace3e3-e189-11e8-b690-01aa75ed71a1/.

European Commission (2023). Supporting policy with scientific evidence, 8 September. https://knowledge4policy.ec.europa.eu/projects-activities/integrated-bioeconomy-land-use-assessment_en#related_reading. Accessed 17 January 2024.

European Environment Agency (2015). *The European Environment State and Outlook 2015: Synthesis Report*. Luxembourg: Publications Office of the European Union.

European Technology Platforms (2011). *The European Bioeconomy in 2030: Delivering Sustainable Growth by Addressing the Grand Societal Challenges*. Oegstgeest. https://www.fabretp.eu/uploads/2/3/1/3/23133976/white-paper-final.pdf.

Eyvindson, K., Repo, A. and Mönkkönen, M. (2018). Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy. *Forest Policy and Economics* 92, 119-127. https://doi.org/10.1016/j.forpol.2018.04.009.

Fang, Z., Smith Jr., R.L. and Qi, X. (eds.). (2017). *Production of Platform Chemicals from Sustainable Resources*. Singapore: Springer Nature Singapore Pte Ltd.

Felgueiras, C., Azoia, N.G., Gonçalves, C., Gama, M. and Dourado, F. (2021). Trends on the cellulose-based textiles: Raw materials and technologies. *Frontiers in Bioengineering and Biotechnology* 9, 608826. https://doi.org/10.3389/fbioe.2021.608826.

Fetting, C. (2020). *The European Green Deal*. Vienna: European Sustainable Development Network Office. https://www.esdn.eu/fileadmin/ESDN_Reports/ESDN_Report_2_2020.pdf.

Finland (2014). *Sustainable Growth From Bioeconomy: The Finnish Bioeconomy Strategy*. Edita Prima Ltd. https://biotalous.fi/wp-content/uploads/2014/08/The_Finnish_Bioeconomy_Strategy_110620141.pdf.

Food and Agriculture Organization of the United Nations (2011a). *State of World's Forests: 2011*. Rome. https://www.fao.org/3/i2000e/i2000e.pdf.

Food and Agriculture Organization of the United Nations (2011b). *The State of the World's Land and Water Resources for Food and Agriculture: Managing Systems at Risk*. Abingdon, Oxford and New York: FAO and Earthscan. https://haseloff.plantsci.cam.ac.uk/resources/SynBio_reports/FAO2011-i1688e.pdf.

Food and Agriculture Organization of the United Nations (2021). Annex 2. Value chain development. In *Evaluation of FAO's Contribution to the Republic of Indonesia 2016-2020: Country Programme Evaluation Series 07/2021*. Rome. https://www.fao.org/3/cb4979en/cb4979en.pdf.

Food and Agriculture Organization of the United Nations (2022). Bioeconomy celebrates World Environment Day, 3 June. https://www.fao.org/in-action/sustainable-and-circular-bioeconomy/resources/news/details/en/c/1538102/. Accessed 11 January 2024.

Food and Agriculture Organization of the United Nations (2023). FAOSTAT Production Crops and Livestock Products. https://www.kaggle.com/datasets/raaad3000/faostat-crops-and-livestock-products. Accessed 11 January 2024.

Forte, A., Zucaro, A., Basosi, R. and Fierro, A. (2016). LCA of 1,4-butanediol produced via direct fermentation of sugars from wheat straw feedstock within a territorial biorefinery. *Materials* 9(7), 563. https://doi.org/10.3390/ma9070563.

Galford, G.L., Melillo, J., Mustard, J.F., Cerri, C.E.P. and Cerri, C.C. (2010). The Amazon frontier of land-use change: Croplands and consequences for greenhouse gas emissions. *Earth Interactions* 14(15), 1-24. https://doi.org/10.1175/2010EI327.1.

García-Velásquez, C., Leduc, S. and van der Meer, Y. (2022). Design of biobased supply chains on a life cycle basis: A bi-objective optimization model and a case study of biobased polyethylene terephthalate (PET). *Sustainable Production and Consumption* 30, 706-719. https://doi.org/10.1016/j.spc.2022.01.003.

Garedew, M. (2018). Towards lignin valorization: Pyrolytic and electrochemical upgrading of lignins extracted from pretreated biomass to valuable intermediates. Doctoral dissertation, Michigan State University.

Garrison, T.F., Murawski, A. and Quirino, R.L. (2016). Bio-based polymers with potential for biodegradability. *Polymers* 8(7), 262. https://doi.org/10.3390/polym8070262.

Garvie, L.C., Roxburgh, S.H. and Ximenes, F.A. (2021). Greenhouse gas emission offsets of forest residues for bioenergy in Queensland, Australia. *Forests* 12(11), 1570. https://doi.org/10.3390/f12111570.

Gebremariam, S.N. and Marchetti, J.M. (2018). Economics of biodiesel production: Review. *Energy Conversion and Management* 168, 74-84. https://doi.org/10.1016/j.enconman.2018.05.002.

Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R.C., Gross, K.L. and Robertson, G.P. (2013). Sustainable bioenergy production from marginal lands in the US Midwest. *Nature* 493(7433), 514-517. https://doi.org/10.1038/nature11811.

Germany (2018). *Coalition Agreement of the 19th Legislative Period of the Bundestag*. https://www.bpb.de/system/files/dokument_pdf/Koalitionsvertrag_2018.pdf.

Germany, Federal Ministry of Education and Research (2011). *National Research Strategy BioEconomy 2030: Our Route Towards a Biobased Economy*. Bonn and Berlin. http://biotech2030.ru/wp-content/uploads/docs/int/bioeconomy_2030_germany.pdf.

Germany, Federal Ministry of Education and Research (2018). *Future Research and Innovation Strategy*. https://www.bpb.de/system/files/dokument_pdf/Koalitionsvertrag_2018.pdf.

Germany, Federal Ministry of Education and Research (2020). *Programme of Germany's Presidency of the Council of the European Union in the Fields of Education, Research and Innovation: Together for Europe's Recovery*. Bonn. https://www.daad-brussels.eu/files/2022/07/Programme_of_Germanys_Presidency_of_the_Council_of_the_European_Union_in_the_Fields_of_Education_Research_and_Innovation.pdf.

Germany, Federal Ministry of Education and Research (n.d.). Future Research and Innovation Strategy. https://www.bmbf.de/bmbf/en/research/future-research-and-innovation-strategy/future-research-and-innovation-strategy.html#searchFacets. Accessed 7 February 2024.

Germany, Federal Ministry of Food and Agriculture (2014). National Bioeconomy Policy Strategy, n.d. https://buel.bmel.de/index.php/buel/article/view/40/Sonderheft-220-EN.html. Accessed 11 January 2024.

Grünig, M., Mazzi, D., Calanca, P., Karger, D.N. and Pellissier, L. (2020). Crop and forest pest metawebs shift towards increased linkage and suitability overlap under climate change. *Communications Biology* 3(1), 233. https://doi.org/10.1038/s42003-020-0962-9.

Guirui, Y., Jianxing, Z., Li, X. and Nianpeng, H. (2022) Technological approaches to enhance ecosystem carbon sink in China: Nature-based solutions. *Bulletin of Chinese Academy of Sciences* 37(4), 490-501. http://old2022.bulletin.cas.cn/publish_article/2022/4/20220408.htm.

Gustavsson, L., Nguyen, T., Sathre, R. and Tettey, U.Y.A. (2021). Climate effects of forestry and substitution of concrete buildings and fossil energy. *Renewable and Sustainable Energy Reviews* 136, 110435. https://doi.org/10.1016/j.rser.2020.110435.

Hakeem, I.G., Sharma, A., Sharma, T., Sharma, A., Joshi, J.B., Shah, K. *et al*. (2023). Techno-economic analysis of biochemical conversion of biomass to biofuels and platform chemicals. *Biofuels, Bioproducts and Biorefining* 17(3), 718-750. https://doi.org/10.1002/bbb.2463.

Hao, H., Ziheng X., Dingjie, L., Jia, Z., Jiaren, Z. and Ling, W. (2019). Industry impact and countermeasures for the promotion and application of sustainable aviation biofuel. *Chemical Industry and Engineering Progress* 38(08), 3497-3507. https://hgjz.cip.com.cn/CN/abstract/abstract7717.shtml.

Hart, J., D'Amico, B. and Pomponi, F. (2021). Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *Journal of Industrial Ecology* 25(2), 403-418. https://doi.org/10.1111/jiec.13139.

Heinimö, J. and Junginger, M. (2009). Production and trading of biomass for energy – An overview of the global status. *Biomass and Bioenergy* 33(9), 1310-1320. https://doi.org/10.1016/j.biombioe.2009.05.017.

Holland, R.A., Eigenbrod, F., Muggeridge, A., Brown, G., Clarke, D. and Taylor, G. (2015). A synthesis of the ecosystem services impact of second generation bioenergy crop production. *Renewable and Sustainable Energy Reviews* 46, 30-40. https://doi.org/10.1016/j.rser.2015.02.003.

Holm-Nielsen, J.B. and Ehimen, E.A. (2014). 4 - Biorefinery plant design, engineering and process optimisation. In *Advances in Biorefineries: Biomass and Waste Supply Chain Exploitation*. Keith Walrdron (ed.). Cambridge, Waltham, MA and Kidlington, Oxford: Woodhead Publishing Limited. Chapter 4. 89-111. https://doi.org/10.1533/9780857097385.1.89.

Huang, K., Peng, X., Kong, L., Wu, W., Chen, Y. and Maravelias, C.T. (2021). Greenhouse gas emission mitigation potential of chemicals produced from biomass. *ACS Sustainable Chemistry & Engineering* 9(43), 14480-14487. https://doi.org/10.1021/acssuschemeng.1c04836.

Hurmekoski, E., Suuronen, J., Ahlvik, L., Kunttu, J. and Myllyviita, T. (2022). Substitution impacts of wood-based textile fibers: Influence of market assumptions. *Journal of Industrial Ecology* 26(4), 1564-1577. https://doi.org/10.1111/jiec.13297.

Immerzeel, B., Vermaat, J.E., Collentine, D., Juutinen, A., Kronvang, B., Skarbøvik, E. *et al*. (2023). The value of change: A scenario assessment of the effects of bioeconomy driven land use change on ecosystem service provision. *CATENA* 223, 106902. https://doi.org/10.1016/j.catena.2022.106902.

Intergovernmental Panel on Climate Change (2019). *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*. Shukla, P.R., Skea, J., Buendía, E.C., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M. and Malley, J. (eds.). Cambridge: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2019/11/SRCCL-Full-Report-Compiled-191128.pdf.

International Energy Agency (2024). Extended World Energy Balances. Paris: OECD Library. https://doi.org/10.1787/data-00513-en. Accessed 24 January 2024.

International Sericultural Commission (2023). Silk Industry – Statistics. https://inserco.org/en/statistics. Accessed 11 January 2024.

Iordan, C.M., Verones, F. and Cherubini, F. (2018). Integrating impacts on climate change and biodiversity from forest harvest in Norway. *Ecological Indicators* 89, 411-421. https://doi.org/10.1016/j.ecolind.2018.02.034.

Japan (2008). *Drastic Reform with Effective and Agile Movements for BT innovation in Japan*. https://www8.cao.go.jp/cstp/project/bt2/bt_01-08.pdf.

Japan (2018). *Integrated Innovation Strategy*. https://www8.cao.go.jp/cstp/english/doc/integrated_main.pdf.

Japan, Prime Minister of Japan and His Cabinet (n.d.) Biotechnology Strategy Council. https://japan.kantei.go.jp/policy/bt/index_e.html. Accessed 10 January 2024.

Jha, P. and Schmidt, S. (2021). State of biofuel development in sub-Saharan Africa: How far sustainable?. *Renewable and Sustainable Energy Reviews* 150, 111432. https://doi.org/10.1016/j.rser.2021.111432.

Ji, X., Liu, Y., Meng, J. and Wu, X. (2020). Global supply chain of biomass use and the shift of environmental welfare from primary exploiters to final consumers. *Applied Energy* 276, 115484. https://doi.org/10.1016/j.apenergy.2020.115484.

Jogi, K. and Bhat, R. (2020). Valorization of food processing wastes and by-products for bioplastic production. Sustainable Chemistry and Pharmacy 18, 100326. https://doi.org/10.1016/j.scp.2020.100326.

Karp, S.G., de Souza Vandenberghe, L.P., Pagnoncelli, M.G.B., Vásquez, Z.S., Martínez-Burgos, W.J., Prado, F. *et al*. (2022). Chapter 7 - Integrated processing of soybean in a circular bioeconomy. In *Biomass, Biofuels, Biochemicals: Circular Bioeconomy – Technologies for Biofuels and Biochemicals*. Amsterdam, Kidlington, Oxford and Cambridge, MA: Elsevier. Chapter 7. 189-216. https://doi.org/10.1016/B978-0-323-89855-3.00007-8.

Kastner, T., Erb, K.-H. and Haberl, H. (2015). Global human appropriation of net primary production for biomass consumption in the European Union, 1986–2007. *Journal of Industrial Ecology* 19(5), 825-836. https://doi.org/10.1111/jiec.12238.

Kline, K.L., Martinelli, F.S., Mayer, A.L., Medeiros, R., Oliveira, C.O.F., Sparovek, G. *et al*. (2015). Bioenergy and Biodiversity: Key Lessons from the Pan American region. *Environmental Management* 56(6), 1377-1396. https://doi.org/10.1007/s00267-015-0559-0.

Koslowski, M., Moran, D.D., Tisserant, A., Verones, F. and Wood, R. (2020). Quantifying Europe's biodiversity footprints and the role of urbanization and income. *Global Sustainability* 3, e1. https://doi.org/10.1017/sus.2019.23.

Kozlowski, R.M. and Mackiewicz-Talarczyk, M. (eds.). (2020). *Handbook of Natural Fibres: Volume 1: Types, Properties and Factors Affecting Breeding and Cultivation*. Cambridge: Woodhead Publishing. https://www.sciencedirect.com/book/9780128183984/handbook-of-natural-fibres.

Kozlowski, R. and Muzyczek, M. (2023). 4 - Hemp, flax and other plant fibres. In *Sustainable Fibres for Fashion and Textile Manufacturing*. Nayak, R. (ed.). Cambridge, MA and Kidlington, Oxford: Woodhead Publishing. Chapter 4. 75-93. https://doi.org/10.1016/B978-0-12-824052-6.00017-2.

Kruitwagen, L., Story, K.T., Friedrich, J., Byers, L., Skillman, S. and Hepburn, C. (2021). A global inventory of photovoltaic solar energy generating units. *Nature* 598(7882), 604-610. https://doi.org/10.1038/s41586-021-03957-7.

Kurukulasuriya, P. and Rosenthal, S. (2013). *Climate Change and Agriculture: A Review of Impacts and Adaptations*. Washington, DC: The World Bank. http://hdl.handle.net/10986/16616.

Lamers, P., Avelino, A.F.T., Zhang, Y., Tan, E.C.D., Young, B., Vendries, J. *et al*. (2021). Potential socioeconomic and environmental effects of an expanding US bioeconomy: An assessment of near-commercial cellulosic biofuel pathways. *Environmental Science & Technology* 55(8), 5496-5505. https://doi.org/10.1021/acs.est.0c08449.

Lammertink, M. (2004). A multiple-site comparison of woodpecker communities in Bornean lowland and hill forests. *Conservation Biology* 18(3), 746-757. https://doi.org/10.1111/j.1523-1739.2004.00046.x.

Lassauce, A., Lieutier, F. and Bouget, C. (2012). Woodfuel harvesting and biodiversity conservation in temperate forests: Effects of logging residue characteristics on saproxylic beetle assemblages. *Biological Conservation* 147(1), 204-212. https://doi.org/10.1016/j.biocon.2012.01.001.

Laurance, W.F., Useche, D.C., Rendeiro, J., Kalka, M., Bradshaw, C.J.A., Sloan, S.P. *et al*. (2012). Averting biodiversity collapse in tropical forest protected areas. *Nature* 489(7415), 290-294. https://doi.org/10.1038/nature11318.

Ladu, L. and Quitzow, R. (2017). Bio-based economy: policy framework and foresight thinking. Food Waste Reduction and Valorisation: *Sustainability Assessment and Policy Analysis*, 167-195. https://doi.org/10.1007/978-3-319-50088-1_9.

Lei, Z., Zelin, L.I., Shuchang, B., Jianhua, W., Hailan, Z. and Chen, Z. (2023). Comprehensive review on green synthesis of bio-based 2,5-furandicarboxylic acid. *Journal of East China Normal University (Natural Science)* 2023(1), 160-169. https://xblk.ecnu.edu.cn/CN/10.3969/j.issn.1000-5641.2023.01.016.

Levasseur, A., Lesage, P., Margni, M. and Samson, R. (2013). Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. *Journal of Industrial Ecology* 17(1), 117-128. https://doi.org/10.1111/j.1530-9290.2012.00503.x.

Liu, J., Li, X., Zhu, L., Xu, X., Huang, Q., Zhang, Y. *et al*. (2023). Discussion on key issues of carbon footprint accounting for bast fiber textiles. *Science of The Total Environment* 897, 166272. https://doi.org/10.1016/j.scitotenv.2023.166272.

Liu, J., Liu, S., Zhu, L., Sun, L., Zhang, Y., Li, X. *et al*. (2023). Carbon neutrality potential of textile products made from plant-derived fibers. *Sustainability* 15(9), 7070. https://doi.org/10.3390/su15097070.

Liu, T., Wang, Q. and Su, B. (2016). A review of carbon labeling: Standards, implementation, and impact. *Renewable and Sustainable Energy Reviews* 53, 68-79. https://doi.org/10.1016/j.rser.2015.08.050.

Longlong, M.A., Zhihua, T., Congwei, W., Yongming, S., Xuefeng, L., Yong, C. *et al* (2019). Current status of biomass energy research and future development strategies. *Bulletin of Chinese Academy of Sciences* 34(4), 434-442. http://old2022.bulletin.cas.cn/publish_article/2019/4/20190409.htm.

Mair, S., Druckman, A. and Jackson, T. (2016). Global inequities and emissions in Western European textiles and clothing consumption. *Journal of Cleaner Production* 132, 57-69. https://doi.org/10.1016/j.jclepro.2015.08.082.

Marin, F.R., Zanon, A.J., Monzon, J.P., Andrade, J.F., Silva, E.H.F.M., Richter, G.L. *et al*. (2022). Protecting the Amazon forest and reducing global warming via agricultural intensification. *Nature Sustainability* 5(12), 1018-1026. https://doi.org/10.1038/s41893-022-00968-8.

Mason, J.E., Yeh, S. and Skog, K.E. (2012). Timing of carbon emissions from global forest clearance. *Nature Climate Change* 2(9), 682-685. https://doi.org/10.1038/nclimate1535.

Mateo-Sagasta, J., Zadeh, S.M. and Turral, H. (2017). *Water Pollution From Agriculture: A Global Review – Executive Summary*. Rome: FAO. https://www.fao.org/3/i7754e/i7754e.pdf.

McCarthy, J.J., Canziani, O.F., Leary, N.A.. Dokken, D.J. and White, K.S. (eds.) (2001). *Climate Change 2001: Impacts, Adaptation, and Vulnerability - Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/03/WGII_TAR_full_report-2.pdf.

McKechnie, J., Colombo, S., Chen, J., Mabee, W. and MacLean, H.L. (2011). Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology* 45(2), 789-795. https://doi.org/10.1021/es1024004.

Meijaard, E., Brooks, T.M., Carlson, K.M., Slade, E.M., Garcia-Ulloa, J., Gaveau, D.L.A. *et al*. (2020). The environmental impacts of palm oil in context. *Nature Plants* 6(12), 1418-1426. https://doi.org/10.1038/s41477-020-00813-w.

Memari, A., Ahmad, R., Abdul Rahim, A.R. and Jokar, M.R.A. (2018). An optimization study of a palm oil-based regional bio-energy supply chain under carbon pricing and trading policies. *Clean Technologies and Environmental Policy* 20(1), 113-125. https://doi.org/10.1007/s10098-017-1461-7.

Milner, S., Holland, R.A., Lovett, A., Sunnenberg, G., Hastings, A., Smith, P. *et al*. (2016). Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. *GCB Bioenergy* 8(2), 317-333. https://doi.org/10.1111/gcbb.12263.

Minowa, T., Kojima, T. and Matsuoka, Y. (2005). Study for utilization of municipal residues as bioenergy resource in Japan. *Biomass and Bioenergy* 29(5), 360-366. https://doi.org/10.1016/j.biombioe.2004.06.018.

Mishra, A., Humpenöder, F., Churkina, G., Reyer, C.P.O., Beier, F., Bodirsky, B.L. *et al*. (2022). Land use change and carbon emissions of a transformation to timber cities. *Nature Communications* 13(1), 4889. https://doi.org/10.1038/s41467-022-32244-w.

Mittal, M., Mittal, D. and Aggarwal, N.K. (2022). Plastic accumulation during COVID-19: Call for another pandemic; bioplastic a step towards this challenge?. *Environmental Science and Pollution Research* 29(8), 11039-11053. https://doi.org/10.1007/s11356-021-17792-w.

Mora, C., Caldwell, I.R., Caldwell, J.M., Fisher, M.R., Genco, B.M. and Running, S.W. (2015). Suitable days for plant growth disappear under projected climate change: Potential human and biotic vulnerability. *PLOS Biology* 13(6), e1002167. https://doi.org/10.1371/journal.pbio.1002167.

Müller-Lindenlauf, M., Deittert, C. and Köpke, U. (2010). Assessment of environmental effects, animal welfare and milk quality among organic dairy farms. *Livestock Science* 128(1-3), 140-148. https://doi.org/10.1016/j.livsci.2009.11.013.

Nabuurs, G.-J., Mrabet, R., Abu Hatab, A., Bustamante, M., Clark, H., Havlik, P. *et al*. (2023). 7 - Agriculture, forestry and other land uses (AFOLU). In *Climate Change 2022: Mitigation of Climate Change – Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Shukla, P.R., Skea, J., Slade, R., Fradera, R., Pathak, M., Al Khourdaijie, A., Belkacemi, M., van Diemen, R., Hasija, A., Lisboa, G., Luz, S., Malley, J., McCollum, D., Some, S. and Vyas, P. (eds.). Cambridge: Cambridge University Press. Chapter 7. 747-860. https://doi.org/10.1017/9781009157926.009.

National Academies of Sciences, Engineering, and Medicine (2020). *Safeguarding the Bioeconomy*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25525.

Neill, C., Coe, M.T., Riskin, S.H., Krusche, A.V., Elsenbeer, H., Macedo, M.N. *et al*. (2013). Watershed responses to Amazon soya bean cropland expansion and intensification. *Philosophical Transactions of the Royal Society B: Biological Sciences* 368(1619), 20120425. https://doi.org/10.1098/rstb.2012.0425.

Ngadi, N. (2013). The employment aspect of palm oil plantation in Indonesia: Challenges and prospects. https://www.researchgate.net/publication/321670297_THE_EMPLOYMENT_ASPECT_OF_PALM_OIL_PLANTATION_IN_INDONESIA_Challenges_and_Prospects/.

Nielsen, A.T., Nord-Larsen, T. and Bentsen, N.S. (2021). CO_2 emission mitigation through fuel transition on Danish CHP and district heating plants. *GCB Bioenergy* 13(7), 1162-1178. https://doi.org/10.1111/gcbb.12836.

Núñez-Regueiro, M.M., Siddiqui, S.F. and Fletcher Jr., R.J. (2021). Effects of bioenergy on biodiversity arising from land-use change and crop type. *Conservation Biology* 35(1), 77-87. https://doi.org/10.1111/cobi.13452.

Nurfatriani, F., Ramawati, Sari, G.K. and Komarudin, H. (2018). *Optimalisasi Dana Sawit dan Pengaturan Instrumen Fiskal Penggunaan Lahan Hutan untuk Perkebunan Dalam Upaya Mengurangi Deforestasi*. Working Paper 238. Bogor Barat: Pusat Penelitian Kehutanan Internasional (CIFOR). https://doi.org/10.17528/cifor/006882.

Organisation for Economic Co-operation and Development (2011). Public Consultation –Draft OECD Recommendation on Assessing the Sustainability of Bio-based Products. Paris. https://renewable-carbon.eu/news/public-consultation-draft-oecd-recommendation-on-assessing-the-sustainability-of-bio-based-products/.

Organisation for Economic Co-operation and Development and Food and Agriculture Organization of the United Nations (2017). OECD-FAO Agricultural Outlook 2017-2026. Paris: OECD Publishing. https://doi.org/10.1787/agr_outlook-2017-en.

Organisation for Economic Co-operation and Development and Food and Agriculture Organization of the United Nations (2022). OECD-FAO Agricultural Outlook 2022-2031. Paris: OECD Publishing. https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2022-2031_f1b0b29c-en.

Ordway, E.M., Naylor, R.L., Nkongho, R.N. and Lambin, E.F. (2019). Oil palm expansion and deforestation in Southwest Cameroon associated with proliferation of informal mills. *Nature Communications* 10(1), 114. https://doi.org/10.1038/s41467-018-07915-2.

Otero, I., Farrell, K.N., Pueyo, S., Kallis, G., Kehoe, L., Haberl, H. *et al*. (2020). Biodiversity policy beyond economic growth. *Conservation Letters* 13(4), e12713. https://doi.org/10.1111/conl.12713.

Overmars, K.P., Stehfest, E., Ros, J.P.M. and Prins, A.G. (2011). Indirect land use change emissions related to EU biofuel consumption: An analysis based on historical data. *Environmental Science & Policy* 14(3), 248-257. https://doi.org/10.1016/j.envsci.2010.12.012.

Paltsev, S.V. (2001). The Kyoto Protocol: Regional and sectoral contributions to the carbon leakage. *The Energy Journal* 22(4), 53-79. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol22-No4-3.

Pavičić, J., Novak Mavar, K., Brkić, V. and Simon, K. (2022). Biogas and biomethane production and usage: Technology development, advantages and challenges in Europe. *Energies* 15(8), 2940. https://doi.org/10.3390/en15082940.

Pelaez-Samaniego, M.R., Haghighi Mood, S., Garcia-Nunez, J., Garcia-Perez, T., Yadama, V. and Garcia-Perez, M. (2022). 2 - Biomass carbonization technologies. In *Sustainable Biochar for Water and Wastewater Treatment*. Mohan, D., Pittman Jr., C.U. and Mlsna, T.E. (eds.). Amsterdam, Kidlington, Oxford and Cambridge, MA: Elsevier. Chapter 2. 39-92. https://doi.org/10.1016/B978-0-12-822225-6.00017-8.

Philp, J. (2018). The bioeconomy, the challenge of the century for policy makers. *New Biotechnology* 40(A), 11-19. https://doi.org/10.1016/j.nbt.2017.04.004.

Popp, J., Lakner, Z., Harangi-Rákos, M. and Fari, M. (2014). The effect of bioenergy expansion: Food, energy, and environment. *Renewable and Sustainable Energy Reviews* 32, 559-578. https://doi.org/10.1016/j.rser.2014.01.056.

Pörtner, H.O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E. *et al*. (eds.) (2022). *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009157964.

Powers, R.P. and Jetz, W. (2019). Global habitat loss and extinction risk of terrestrial vertebrates under future land-use-change scenarios. *Nature Climate Change* 9(4), 323-329. https://doi.org/10.1038/s41558-019-0406-z.

Pydimalla, M., Husaini, S., Kadire, A. and Verma, R.J. (2023). Sustainable biodiesel: A comprehensive review on feedstock, production methods, applications, challenges and opportunities. *Materials Today: Proceedings* 92(2), 458-464. https://doi.org/10.1016/j.matpr.2023.03.593.

Qiu, J., Shen, Z., Leng, G. and Wei, G. (2021). Synergistic effect of drought and rainfall events of different patterns on watershed systems. *Scientific Reports* 11(1), 18957. https://doi.org/10.1038/s41598-021-97574-z.

Raymond, C., Horton, R.M., Zscheischler, J., Martius, O., AghaKouchak, A., Balch, J. *et al*. (2020). Understanding and managing connected extreme events. *Nature Climate Change* 10(7), 611-621. https://doi.org/10.1038/s41558-020-0790-4.

Reijnders, L. (2006). Conditions for the sustainability of biomass based fuel use. *Energy Policy*, 34(7), 863-876. https://doi.org/10.1016/j.enpol.2004.09.001.

Reijnders, L. (2013). Sustainability of soil fertility and the use of lignocellulosic crop harvest residues for the production of biofuels: A literature review. *Environmental Technology* 34(13-14), 1725-1734. https://doi.org/10.1080/09593330.2013.826252.

Robati, M. and Oldfield, P. (2022). The embodied carbon of mass timber and concrete buildings in Australia: An uncertainty analysis. *Building and Environment* 214, 108944. https://doi.org/10.1016/j.buildenv.2022.108944.

Rosner, H. (2018). Palm oil is unavoidable. Can it be sustainable?, 12 April. https://www.nationalgeographic.com/magazine/article/palm-oil-products-borneo-africa-environment-impact. Accessed 11 January 2024.

Roy, K., Debnath, S.C. and Potiyaraj, P. (2020). A review on recent trends and future prospects of lignin based green rubber composites. *Journal of Polymers and the Environment* 28(2), 367-387. https://doi.org/10.1007/s10924-019-01626-5.

Rulli, M.C., Casirati, S., Dell'Angelo, J., Davis, K.F., Passera, C. and D'Odorico, P. (2019). Interdependencies and telecoupling of oil palm expansion at the expense of Indonesian rainforest. *Renewable and Sustainable Energy Reviews* 105, 499-512. https://doi.org/10.1016/j.rser.2018.12.050.

Santika, T., Wilson, K.A., Budiharta, S., Law, E.A., Poh, T.M., Ancrenaz, M. *et al*. (2019). Does oil palm agriculture help alleviate poverty? A multidimensional counterfactual assessment of oil palm development in Indonesia. *World Development* 120, 105-117. https://doi.org/10.1016/j.worlddev.2019.04.012.

Schaffel, S., Herrera, S., Obermaier, M. and Lèbre La Rovere, E. (2012). Can family farmers benefit from biofuel sustainability standards? Evidence from the Brazilian Social Fuel Certificate. *Biofuels* 3(6), 725-736. https://doi.org/10.4155/bfs.12.67.

Schulze, E.D., Körner, C., Law, B.E., Haberl, H. and Luyssaert, S. (2012). Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *GCB Bioenergy* 4(6), 611-616. https://doi.org/10.1111/j.1757-1707.2012.01169.x.

Scotti, A., Fureder, L., Marsoner, T., Tappeiner, U., Stawinoga, A.E. and Bottarin, R. (2020). Effects of land cover type on community structure and functional traits of alpine stream benthic macroinvertebrates. *Freshwater Biology* 65(3), 524-539. https://doi.org/10.1111/fwb.13448.

Skarbøvik, E., Jordan, P., Lepistö, A., Kronvang, B., Stutter, M.I. and Vermaat, J.E. (2020). Catchment effects of a future Nordic bioeconomy: From land use to water resources. *Ambio* 49(11), 1697-1709. https://doi.org/10.1007/s13280-020-01391-z.

Smyth, C., Rampley, G., Lemprière, T.C., Schwab, O. and Kurz, W.A. (2017). Estimating product and energy substitution benefits in national-scale mitigation analyses for Canada. *GCB Bioenergy* 9(6), 1071-1084. https://doi.org/10.1111/gcbb.12389.

Solheim, A.L., Tolvanen, A., Skarbøvik, E., Kløve, B., Collentine, D., Kronvang, B. *et al*. (2023). Land-use change in a Nordic future towards bioeconomy: A methodological framework to compare and merge stakeholder and expert opinions on qualitative scenarios. *CATENA* 228, 107100. https://doi.org/10.1016/j.catena.2023.107100.

South Africa (2001). *A National Biotechnology Strategy for South Africa*. https://www.gov.za/sites/default/files/gcis_document/201409/biotechstrat0.pdf.

South Africa, Department of Science and Technology (2013). *The Bio-Economy Strategy*. https://www.gov.za/sites/default/files/gcis_document/201409/bioeconomy-strategya.pdf.

Stegmann, P., Daioglou, V., Londo, M., van Vuuren, D.P. and Junginger, M. (2022). Plastic futures and their CO_2 emissions. *Nature* 612(7939), 272-276. https://doi.org/10.1038/s41586-022-05422-5.

Stellingwerf, H.M., Guo, X., Annevelink, E. and Behdani, B. (2022). Logistics and supply chain modelling for the biobased economy: A systematic literature review and research agenda. *Frontiers in Chemical Engineering* 4, 778315. https://doi.org/10.3389/fceng.2022.778315.

Statista (2023). Leading Cotton Producing Countries Worldwide in 2022/2023. Statista. https://www.statista.com/statistics/263055/cotton-production-worldwide-by-top-countries/. Accessed 24 January 2024.

Strapasson, A., Woods, J., Chum, H., Kalas, N., Shah, N. and Rosillo-Calle, F. (2017). On the global limits of bioenergy and land use for climate change mitigation. *GCB Bioenergy* 9(12), 1721-1735. https://doi.org/10.1111/gcbb.12456.

Sun, M., Wang, Y. and Shi, L., (2018). Environmental performance of straw-based pulp making: A life cycle perspective. *Science of the Total Environment* (616-617), 753-762. https://doi.org/10.1016/j.scitotenv.2017.10.250.

Sun, M., Wang, Y., Shi, L. and Klemeš, J.J. (2018). Uncovering energy use, carbon emissions and environmental burdens of pulp and paper industry: A systematic review and meta-analysis. *Renewable and Sustainable Energy Reviews* 92, 823-833. https://doi.org/10.1016/j.rser.2018.04.036.

Tabe-Ojong, M.P.J., Lokossou, J.C., Gebrekidan, B. and Affognon, H.D. (2023). Adoption of climate-resilient groundnut varieties increases agricultural production, consumption, and smallholder commercialization in West Africa. *Nature Communications* 14(1), 5175. https://doi.org/10.1038/s41467-023-40781-1.

Taheripour, F., Hertel, T.W. and Ramankutty, N. (2019). Market-mediated responses confound policies to limit deforestation from oil palm expansion in Malaysia and Indonesia. *Proceedings of the National Academy of Sciences* 116(38), 19193-19199. https://doi.org/10.1073/pnas.1903476116.

Tang, K.H.D. and Al Qahtani, H.M.S. (2020). Sustainability of oil palm plantations in Malaysia. *Environment, Development and Sustainability* 22(6), 4999-5023. https://doi.org/10.1007/s10668-019-00458-6.

Tezer, Ö., Karabağ, N., Öngen, A., Çolpan, C.Ö. and Ayol, A. (2022). Biomass gasification for sustainable energy production: A review. *International Journal of Hydrogen Energy* 47(34), 15419-15433. https://doi.org/10.1016/j.ijhydene.2022.02.158.

Thomas, J.-B.E., Sinha, R., Strand, Å., Söderqvist, T., Stadmark, J., Franzén, F. *et al*. (2022). Marine biomass for a circular blue-green bioeconomy? A life cycle perspective on closing nitrogen and phosphorus land-marine loops. *Journal of Industrial Ecology* 26(6), 2136-2153. https://doi.org/10.1111/jiec.13177.

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L. *et al*. (2009). Beneficial biofuels–The food, energy, and environment trilemma. *Science* 325(5938), 270-271. https://doi.org/10.1126/science.1177970.

Többen, J.R., Distelkamp, M., Stöver, B., Reuschel, S., Ahmann, L. and Lutz, C. (2022). Global land use impacts of bioeconomy: An econometric input–output approach. *Sustainability* 14(4), 1976. https://doi.org/10.3390/su14041976.

Tripathi, N., Hills, C.D., Singh, R.S. and Atkinson, C.J. (2019). Biomass waste utilisation in low-carbon products: Harnessing a major potential resource. *NPJ Climate and Atmospheric Science* 2(1), 35. https://doi.org/10.1038/s41612-019-0093-5.

United Kingdom (2015). *Building a High Value Bioeconomy: Opportunities From Waste*. London. https://assets.publishing.service.gov.uk/media/5a7f7c9ce5274a2e8ab4c78e/BIS-15-146_Bioeconomy_report_-_opportunities_from_waste.pdf.

United Kingdom, Department for Business, Energy and Industrial Strategy (2017). *The Clean Growth Strategy: Leading the Way to a Low Carbon Future*. London. https://unfccc.int/sites/default/files/resource/clean-growth-strategy-amended-april-2018.pdf.

United Kingdom, Department of Energy and Climate Change (2012). *UK Bioenergy Strategy*. London. https://assets.publishing.service.gov.uk/media/5a79806340f0b642860d8a1a/5142-bioenergy-strategy-.pdf.

United Kingdom, Department for Environment, Food and Rural Affairs (2011). *The Natural Choice: Securing the Value of Nature*. United Kingdom: The Stationery Office Limited. https://assets.publishing.service.gov.uk/media/5a7cb8fce5274a38e57565a4/8082.pdf.

United Nations (2009). *Women, Gender Equality and Climate Change* [factsheet]. https://www.un.org/womenwatch/feature/climate_change/downloads/Women_and_Climate_Change_Factsheet.pdf. Accessed 12 January 2024.

United Nations Environment Programme, United Nations Entity for Gender Equality and the Empowerment of Women, United Nations Peacebuilding Support Office and United Nations Development Programme (2013). *Women and Natural Resources: Unlocking the Peacebuilding Potential*. Nairobi and New York. https://www.un.org/peacebuilding/sites/www.un.org.peacebuilding/files/documents/women_and_nrm_report.pdf.

United States of America, Biomass Research and Development Board (2016). *The Billion Ton Bioeconomy Initiative: Challenges and Opportunities*. https://www.wctsservices.usda.gov/Energy/resources/TheBioeconomyInitiative_20161109.pdf.

United States of America, Department of Agriculture (n.d.). Biopreferred. https://www.biopreferred.gov/BioPreferred/. Accessed 11 January 2024.

United States of America, Department of the Interior and Department of Agriculture (n.d.). Woody biomass utilization and the WBUG: What is woody biomass utilization?. https://www.forestsandrangelands.gov/woody-biomass/overview.shtml.

United States of America, White House (2012). National bioeconomy blueprint, April 2012. *Industrial Biotechnology* 8(3), 97-102. https://doi.org/10.1089/ind.2012.1524.

United States of America, White House, Office of Science and Technology Policy (2019). *Summary of the 2019 White House Summit on America's Bioeconomy*. https://trumpwhitehouse.archives.gov/wp-content/uploads/2019/10/Summary-of-White-House-Summit-on-Americas-Bioeconomy-October-2019.pdf.

United States, Department of Agriculture Economic Research Service and Office of the Chief Economist (2011). *Measuring the Indirect Land-Use Change Associated with Increased Biofuel Feedstock Production: A Review of Modeling Efforts – Report to Congress*. https://ageconsearch.umn.edu/record/292118.

van der Geest, K. and van den Berg, R. (2021). Slow-onset events: A review of the evidence from the IPCC Special Reports on Land, Oceans and Cryosphere. *Current Opinion in Environmental Sustainability* 50, 109-120. https://doi.org/10.1016/j.cosust.2021.03.008.

van Evert, F.K., de Ruijter, F.J., Conijn, J.G., Rutgers, B. and Haverkort, A.J. (2013). Worldwide sustainability hotspots in potato cultivation. 2. Areas with improvement opportunities. *Potato Research* 56(4), 355-368. https://doi.org/10.1007/s11540-013-9248-7.

Vermaat, J.E., Skarbøvik, E., Kronvang, B., Juutinen, A., Hellsten, S., Kyllmar, K. *et al*. (2023). Projecting the impacts of the bioeconomy on Nordic land use and freshwater quality and quantity – An overview. *CATENA* 228, 107054. https://doi.org/10.1016/j.catena.2023.107054.

Victorsson, J. and Jonsell, M. (2013). Ecological traps and habitat loss, stump extraction and its effects on saproxylic beetles. *Forest Ecology and Management* 290, 22-29. https://doi.org/10.1016/j.foreco.2012.06.057.

Villoria, N., Garrett, R., Gollnow, F. and Carlson, K. (2022). Leakage does not fully offset soy supply-chain efforts to reduce deforestation in Brazil. *Nature Communications* 13(1), 5476. https://doi.org/10.1038/s41467-022-33213-z.

Wagner, M., Wentz, E.A. and Stuhlmacher, M. (2022). Quantifying oil palm expansion in Southeast Asia from 2000 to 2015: A data fusion approach. *Journal of Land Use Science* 17(1), 26-46. https://doi.org/10.1080/1747423X.2021.2020918.

Wang, S., Chen, J., Ter-Mikaelian, M.T., Levasseur, A. and Yang, H. (2022). From carbon neutral to climate neutral: Dynamic life cycle assessment for wood-based panels produced in China. *Journal of Industrial Ecology* 26(4), 1437-1449. https://doi.org/10.1111/jiec.13286.

Wang, H.G. (2004). A brief discussion on “bioeconomy”. Life Science Instruments 2(3), 40-44. https://www.cnki.net/KCMS/detail/detail.aspx?dbname=cjfd2004&filename=sbky200403020&dbcode=cjfq.

Wang, S., Cheng, A., Liu, F., Zhang, J., Xia, T., Zeng, X. *et al*. (2023). Catalytic conversion network for lignocellulosic biomass valorization: A panoramic view. *Industrial Chemistry & Materials* 1(2), 188-206. https://doi.org/10.1039/D2IM00054G.

Wang, W. and Khanna, M. (2023). Land use effects of biofuel production in the US. *Environmental Research Communications* 5(5), 055007. https://doi.org/10.1088/2515-7620/acd1d7.

Wei, H., Liu, W., Chen, X., Yang, Q., Li, J. and Chen, H. (2019). Renewable bio-jet fuel production for aviation: A review. *Fuel* 254, 115599. https://doi.org/10.1016/j.fuel.2019.06.007.

Welfle, A., Gilbert, P. and Thornley, P. (2014). Increasing biomass resource availability through supply chain analysis. *Biomass and Bioenergy* 70, 249-266. https://doi.org/10.1016/j.biombioe.2014.08.001.

Werling, B.P., Dickson, T.L., Isaacs, R., Gaines, H., Gratton, C., Gross, K.L. *et al*. (2014). Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. *PNAS* 111(4), 1652-1657. https://doi.org/10.1073/pnas.1309492111.

Werpy, T., Petersen, G., Aden, A., Bozell, J., Holladay, J., White, J. *et al*. (2004). *Top Value Added Chemicals From Biomass: Volume I– Results of Screening for Potential Candidates from Sugars and Synthesis Gas*. https://www.nrel.gov/docs/fy04osti/35523.pdf.

West, P.C., Gibbs, H.K., Monfreda, C., Wagner, J., Barford, C.C., Carpenter, S.R. *et al*. (2010). Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. *Proceedings of the National Academy of Sciences* 107(46), 19645-19648. https://doi.org/10.1073/pnas.1011078107.

Whited, G.M., Feher, F.J., Benko, D.A., Cervin, M.A., Chotani, G.K., McAuliffe, J.C. *et al*. (2010). Technology update: Development of a gas-phase bioprocess for isoprene-monomer production using metabolic pathway engineering. *Industrial Biotechnology* 6(3), 152-163. https://doi.org/10.1089/ind.2010.6.152.

Wiloso, E.I., Heijungs, R. and de Snoo, G.R. (2012). LCA of second generation bioethanol: A review and some issues to be resolved for good LCA practice. *Renewable and Sustainable Energy Reviews* 16(7), 5295-5308. https://doi.org/10.1016/j.rser.2012.04.035.

Winter, B., Meys, R. and Bardow, A. (2021). Towards aromatics from biomass: Prospective Life Cycle Assessment of bio-based aniline. *Journal of Cleaner Production* 290, 125818. https://doi.org/10.1016/j.jclepro.2021.125818.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R. *et al*. (2009). Implications of limiting CO_2 concentrations for land use and energy. *Science* 324(5931), 1183-1186. https://doi.org/10.1126/science.1168475.

World Bank (2022). Urban development: Overview, 6 October. https://www.worldbank.org/en/topic/urbandevelopment/overview. Accessed 10 January 2024.

World Trade Organization (2021). *Why Cotton? Facts and Figures* [infographic]. https://www.wto.org/english/tratop_e/agric_e/wcd_2020_fact_and_figures_e.pdf. Accessed 11 January 2024.

World Wildlife Fund (2024). Palm oil. https://www.worldwildlife.org/industries/palm-oil. Accessed 10 January 2024.

Xiao, Y.X. (2020). Selective synthesis of bio-based aromatics from biomass-derived. Masters dissertation, Hunan Normal University, in Chinese. https://doi.org/10.27137/d.cnki.ghusu.2020.002833.

Xu, J., Gao, J., de Holanda, H.V., Rodríguez, L F., Caixeta-Filho, J.V., Zhong, R. *et al*. (2021). Double cropping and cropland expansion boost grain production in Brazil. *Nature Food* 2(4), 264-273. https://doi.org/10.1038/s43016-021-00255-3.

Xu, Y., Yu, L., Ciais, P., Li, W., Santoro, M., Yang, H. *et al*. (2022). Recent expansion of oil palm plantations into carbon-rich forests. *Nature Sustainability* 5(7), 574-577. https://doi.org/10.1038/s41893-022-00872-1.

Yang, L., Wu, Y., Yang, F., Wu, X., Cai, Y. and Zhang, J. (2021). A wood textile fiber made from natural wood. *Journal of Materials Science* 56(27), 15122-15133. https://doi.org/10.1007/s10853-021-06240-2.

Yu, J.L., Zhou, L.L. and Hu, H.Q. (2018). Historical characteristics and future trend prediction of carbon emissions in China’s civil aviation. *Sino-Global Energy*, 23(8), 10-15. https://kns.cnki.net/kcms2/article/abstract?v=lj1AjTyXPBu4II7gx-AldrrVTDKYfFm2PDWcGLLeiA3DhC2HlnxHNCfJE3Egq1qoviV0x1sQJPQSAy_EUOsojtGepE0E4jpx-kz1K8U-BkOu-zVyMP651kASEU6j2zzxJjjLaAb0lGiVI02Q7Ea7wA==&uniplatform=NZKPT.

Yuan, J.Z. and Zhu, T. (2018). Overview of biomass energy utilization technologies and policies. *China Energy* 40(6), 6. http://gjs.cass.cn/kydt/kydt_kycg/201807/t20180703_4493610.shtml.

Zaborowska, M. and Bernat, K. (2023). The development of recycling methods for bio-based materials – A challenge in the implementation of a circular economy: A review. *Waste Management and Research* 41(1), 68-80. https://doi.org/10.1177/0734242X221105432.

Zanchi, G., Pena, N. and Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy* 4(6), 761-772. https://doi.org/10.1111/j.1757-1707.2011.01149.x.

Zapata, C., Vazquez-Brust, D. and Plaza-Úbeda, J. (2010). *Productive Inclusion of Smallholder Farmers in Brazil’s Biodiesel Value Chain: Programme Design, Institutional Incentives And Stakeholder Constraints*. Brazil: International Policy Centre for Inclusive Growth and United Nations Development Programme. http://hdl.handle.net/10419/71825.

Zhang, Z., Huang, J., Yao, Y., Peters, G., Macdonald, B., La Rosa, A.D. *et al*. (2023). Environmental impacts of cotton and opportunities for improvement. *Nature Reviews Earth & Environment* 4(10), 703-715. https://doi.org/10.1038/s43017-023-00476-z.

UN environment programme

United Nations Avenue, Gigiri
P.O. Box 30552, 00100 Nairobi, Kenya
Tel. +254 20 762 1234
unep-publications@un.org
www.unep.org