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Perspective

Towards a sustainable bioeconomy in a post-oil era Nigeria

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ABSTRACT

The bioeconomy comprises all primary arms of production, including industrial and economic sectors that employ biological resources and techniques to generate bio-based products and services, while creating new industries and employment. Advocates of the bioeconomy anticipate that biotechnology will play a key role in its development via scientific advances that will spur innovations in deriving products and energy from renewable biomass. About 50 countries have adopted bioeconomy policies, with a view to unlocking new vistas for economic development and innovation, while pushing towards the attainment of the United Nations Sustainable Development Goals (SDGs). Nigeria has an estimated annual biomass potential of about 200 billion kilogrammes, which could be harnessed to generate biofuels via integrated bio-refineries and microbial conversion. In addition, alternative food sources from microorganisms, aquaponics and other products from wood, especially as a plastic alternative and medicines provide endless opportunities for a sustainable bioeconomy in Nigeria.

1. Introduction

The prehistoric era saw humans' reliance on primary forms of energy resources (Ritchie et al., 2020). However, population explosion and the quest to sustain the same led to significant shifts in the magnitude and type of energy required to perform work and meet man's needs (Wrigley, 2013). The industrial revolution of the mid-19th century ushered in the use of fossil fuels. In addition to driving socio-economic and technological advancement in Europe and the United States following its discovery, fossil fuels have continued to occupy a dominant position in the global energy market. Its large-scale utilization since the mid-20th century has nevertheless brought along with it negative consequences (Ritchie et al., 2020). The combustion of fossil fuels to generate energy contributes up to 80% of greenhouse gas emissions (GHG), and elevates global warming which is disrupting crucial plant nutrient cycles, steering biodiversity loss, and causing ruins to agricultural crop productivity (Perea-Moreno et al., 2020). The situation is projected to worsen with the rising human population that is predicted to reach 9 billion by the year 2050 (Roe et al., 2019), hence the need to replace fossil fuels with more efficient, renewable, and safer energy sources. For instance, the transformation of land use for bioenergy, forestry, agriculture, and wetlands could contribute approximately 30% of the greenhouse gas mitigation required by 2050 (Roe et al., 2019). The Lund declaration of July 8, 2009, spotlighted the need for European research and innovation to concentrate on the major challenges facing the global community, and pursue sustainable solutions in priority areas related to public health, pandemics, ageing societies, climate change, security and the increasingly difficult access to cleaner energy, water and food sources (Circle, 2020). One major highlight of the declaration was to develop an eco-efficient European economy built around renewable, biodegradable, and sustainable plant organic matter (Lund Declaration, 2009; Bjelland, 2020). In alignment with Lund's declaration, the idea of a bioeconomy was advanced by prominent corporations with the backing of the EU and G7 nations. Bioeconomy, according to the Global Bioeconomy Summit (2020), is the conservation, production, utilization, and regeneration of bioresources, in addition to allied technologies, science, knowledge, and innovation to proffer lasting solutions across and within all economic sectors, and facilitate a transformation to a sustainable economy. Advocates of the bioeconomy concept anticipate that biotechnology will make major contributions to its development via innovations in deriving products and energy from renewable biomass (Bracco et al., 2018; Befort, 2020).

In line with their respective political pursuits, the US, the EU, and several international bodies have individually designed comprehensive blueprints and adopted the bioeconomy as a viable approach for unlocking new prospects for economic development and innovation, as well as achieving the sustainable development goals (SDGs) (FAO,

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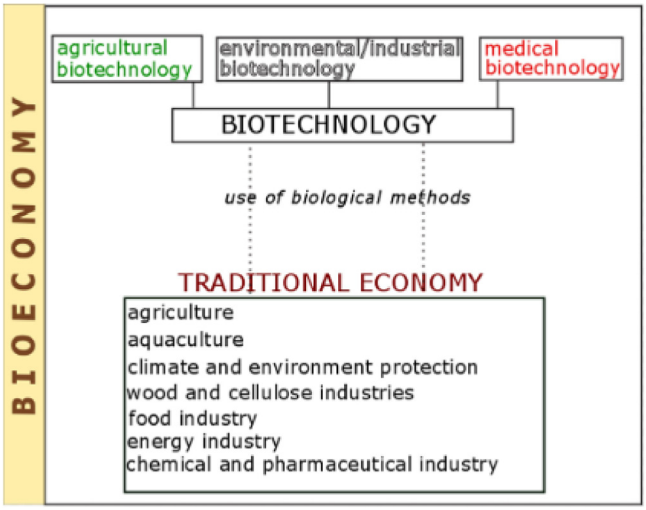

Fig. 1. Bioeconomy sectors (Woźniak and Twardowski, 2018).

2018; Heimann, 2019; Pandey, 2021). While South Africa boasts of a clearly defined bioeconomy plan, Nigeria is still lagging behind, despite an abundance of biomass resources.

This perspective article discusses the bioeconomy as an emerging paradigm, with biotechnology contributing a major role. It also highlights the contributions of the bioeconomy to the economies of developed and developing nations. Furthermore, the paper looks at the current state of Africa's bioeconomy, with special focus on Nigeria, and then highlights how Nigeria can leverage technological innovations and its abundant biomass resources to foster a transition to bioeconomy in a post-oil era.

2. Biotechnology as the foundation of the bioeconomy

The bioeconomy entails the large-scale application of biotechnology (Aguilar et al., 2019). Breakthroughs including DNA sequencing, high-throughput molecular operations, the capacity to read genetic codes, modify genomes and metabolic pathways to develop organisms with wholly synthetic genomes, and nanotechnology have significantly increased the possibility of biotechnology to drive the bioeconomy (Frisvold et al., 2021). Biotechnology, which in terms of revenue is worth more than USD 300 billion, has become one of the core technologies for supporting a new green and sustainable bioeconomy, with solutions for a wide range of sectors, including energy, environment, agri-food, and circular economy. As a result, biotechnology offers potential for long-term economic growth through job creation, maintaining living standards, energy generation, and new bio-products development (Aguilar et al., 2009). The bioeconomy also encompasses the traditional sectors of the economy which produce services and bio-products using biotechnologies (Woźniak and Twardowski, 2018) (Fig. 1).

3. Recent trends in bioeconomy

It is now recognized that the traditional linear economy model, which relies on the unsustainable utilization of non-renewable fossil-fuel resources and allied products poses a risk to the environment and societies due to adverse consequences such as ecosystems degradation and climate change (Bracco et al., 2018). Established on the take-make-dispose model, the linear economy is less efficient at resource exploitation, and generates high levels of waste. Current economic and environmental trends have evidently displayed that the blueprint of the linear economy has reached its tipping point. Therefore, an unavoidable, viable and sustainable alternative of bioeconomy becomes desirable (Sariatli, 2017). The term bioeconomy in the 1980's, was used to depict a solar energy-driven sustainable economy, which fits within the confines of ecology without the permanent contriant to grow (Gawel et al., 2019). In the 1990s, a redefintion of the bioeconomy was advanced. It was described as an "economic sector that makes use of new biological knowledge for industrial and commercial purposes" (Gawel et al., 2019). This definition, alongside the corresponding establishment of the 2002 Strategy on Biotechnology sets the stage for the "Knowledge-based Bioeconomy" (KBBE) in 2005 (Gawel et al., 2019). A conference report of the European Commission (EC) defined the KBBE as a sustainable economy built around renewable resources, which would not only contribute to developing more ecologically safe production systems and expanding the frontiers of science (Birner, 2018), but also assure the availability of resources during periods of shrinking oil supplies (Gawel et al., 2019). More recently, the European Commission (2018) defined the bioeconomy as an economy that uses renewable biological resources from the land and sea (e.g., animals, crops, fish, forests and microorganisms) to produce energy, food and materials (D'Adamo et al., 2022). Modern bioeconomy should not focus only on biomass and substitution of fossil fuels with sustainable and renewable alternatives, but should be targeted towards "biologisation" of the economy via disruptive innovations that convert bioresources into food, feed, products, and services that integrate sustainability (Global Bioeconomy Summit, 2020). Globally, over 50 countries now have bioeconomy-related initiatives (Aguilar et al., 2019). In 2014, about USD 2 trillion worth of bio-based foods, fuels, and products were shipped, accounting for 13% of global commerce, up from 10% in 2007 (El-Chichakli et al., 2016). Many poor and middle-income nations are beginning to adopt the bioeconomy as an approach to unlock new prospects for economic growth and for achieving the United Nations' SDGs (FAO, 2018). A sustainable bioeconomy therefore must emphasize the use of resources as long and as efficiently as possible, with minimal or reused waste, leading to the concept of a "circular bioeconomy" (CE) (Stratan, 2017; Ranjbari et al., 2022). The recognition that the bioeconomy is to a great degree coupled to circularity was reinforced by the concept of "circular bioeconomy"(CBE). This laid the foundation for the European Commission's vision of the bioeconomy, which incoporates the idea of renewability, sustainability, and circularity, with a view to cut back on waste, while advancing towards a closed-loop economy (Ranjbari et al., 2022). Policy makers in the European Union (EU) have tipped the concept of sustainable development and CBE as high priority models that can expedite the attainment of the United Nations sustainable development goals (SDGs) (Kardung et al., 2021; D'Adamo and Sassanelli, 2022). The CBE or bio-based CE is built around the efficient and sustainable valorization of biomass (Ranjbari et al., 2022) via integrated and multiple product production chains, while utilizing waste and optimizing biomass value over time through cascades (Rodríguez, 2022). Being a carbon neutral renewable energy source of plant or animal origin, biomass has been widely investigated by scholars within the context of the establishment of a CE and CBE. Consequently, a broad knowledge by key players of the benefits of biomass utility and its implications along the entire value chain is a prerequisite for a successful transition towards a CBE (Ranjbari et al., 2022). Biorefineries, which are facilities for transforming different biomass feedstocks to a sundry of high premium bio-based products are pivotal to the establishment of the bioeconomy (Ranjbari et al., 2022). The generation of biofuels and other materials from food waste-based biorefineries has been touted as an avenue to combat the problems of resource scarcity, climate change, price volatility and increasing demand (Ranjbari et al., 2022). By incorporating waste engineering processes into city designing, Europe's HOOP project (https://hoopproject.eu/) is converting urban bio-waste and wastewater into bio-based products, and transforming cities into urban CBE centers (Global Bioeconomy Summit, 2020).

Table 1
Outcomes of the bioeconomy on the SDGs.

SDG	Description	Effect of bioeconomic activities on SDGs	References
1 2	No poverty No hunger	Socio-economic outcomes. The agricultural product market and agricultural output are generally affected by the bioeconomy through advances in the areas of plant and animal breeding, farming and cultivation techniques, food shelf-life extension and revival of indigenous crops.	Heimann (2019); El-Chichakli et al. (2016)
3	Good health and wellbeing	Socio-economic outcomes. Good health and wellbeing are affected by investments into biotechnology research driven by bioeconomic concepts. In 2009, about 80% of the biotechnology research investments by public and private sectors were recorded in medical and pharmaceutical applications.	Heimann (2019)
6	Sanitation and clean water	Ecological outcomes related to SDGs 13,14 and 15	Heimann (2019)
7	Clean and affordable energy	Industrial and economic outcomes related to SDGs 9 and 12.	Heimann (2019)
8	Economic growth and decent work	Socio-economic outcomes. The job market is affected by the bioeconomy through innovations that lead to value addition, commercialization and industrialization	Heimann (2019)
9 12	Infrastructure and Industry innovation Responsible production and consumption	Industrial and economic outcomes. SDGs 7, 9, and 12 consider the production of energy goods from biological sources, which consequently, relates to the sustainable utilization of global bio-based resources.	Heimann (2019)
13 14 15	Climate action Life below water Life on land	Ecological outcomes. SDGs 6, 13, 14, 15 are affected by the bioeconomy, as they incorporate the effects of agricultural and industrial activities on water, oceans, land and the atmosphere.	Heimann (2019)

Only few industries have adopted a manufacturing model that efficiently and effectively utilize materials and energy. It therefore becomes crucial to assess and measure the circularity performances of manufacturing systems. By assessing resource flows, it is possible to devise solutions to attenuate environmental impact and while simultaneously boosting economic savings. The CE does not connote only system optimization and industrial symbiosis, but also life cycle optimization. With respect to a "self-sustaining economy", it is imperative to work at single product- and system level at the same time, with the objective of analysing in detail, the single resource flow and single production phase. This way, it will be possible to identify where improvements are. For this reason, a quantitative analysis model must be proposed with the aim of keeping the product as the main subject of the analysis with regards to the CE, and to determine the degree of circularity (Sassanelli et al., 2019). In their work, Acerbi et al. (2022) conceptualized a reference data model to aid the process of decision-making by manufacturers while adopting circular manufacturing (CM). According to the authors, the model creates and increases the consciousness of manufacturers about data needed to adopt CM, and at the same time prompts responsiveness regarding the need to deploy both external and internal data to achieve sucesss. Armed with this broad perspective, manufacturers are acquainted with the kind of data needed in CM, how the unavailability of specific data can negatively affect the circularity of resources, and how resources from external systems can be utilized where information are available.

4. Bioeconomy and the SDGs

The bioeconomy is a crucial component for connecting and empowering people towards achieving the SDGs. Sustainable development is the development that fulfils the needs of the present generation without endangering the capacity of future generations to meet their own needs (Brundtland Report, 1987, http://www.un-documents.net/our-common-future.pdf). The three primary aspects to sustainable development: environment, society and economy are well articulated in the SDGs global framework, launched by the United Nations in 2015, and have become important indicators in the strive towards sustainable development (Kardung et al., 2021). The work of Heimann (2019) identified SDGs 1 to 3, 6 to 9, and 12 to 15 to be affected by bioeconomy activities. The author summarized the outcomes of the bioeconomy on the SDGs into three categories of: ecological, industrial and economic, and socio-economic dimensions (Table 1).

5. Economic impacts of the bioeconomy in the EU, US and Asia

In alignment with the SDGs, the bioeconomy is being adopted as a viable approach to unlock new opportunities for economic growth, employment, promotion of value addition to bioresources, food and energy security, sustainability and climate change mitigation (FAO, 2018), with well over 50 countries now having bioeconomy-related blueprints (Aguilar et al., 2019). The Finnish government published a success story of its bioeconomy in 2014 and showed that it exceeded EUR 60 billion, contributed more than 16% to the country's gross domestic product (GDP), and created more than 300,000 jobs. The objective of Finland's Bioeconomy Strategy is to increase the output of its bioeconomy to EUR 100 billion and create 100,000 new jobs by 2025 (https://biotalous.fi/wp-content/uploads/2014/08/The_Finnish_Bioeconomy_Strategy_110620141.pdf). Likewise, Germany's overall bioeconomy sector revenue was EUR 386 billion in 2015, ranking first among EU member states, with 1.96 million people employed. A report by the United States' National Academies of Sciences, Engineering, and Medicine (NASEM), examined data and methods to evaluate the contributions of the bioeconomy to the US economy in general. The direct contribution to GDP was estimated (based on 2016 data) to be USD 402.5 billion. However, including indirect contribution and induced multiplier effects, the total contribution of the bioeconomy to US GDP was estimated to be nearly a trillion dollars (USD 952.2 billion) (NASEM, 2020). Argentina's bioeconomy accounted for 15.4% of its GDP in 2012, with a total value-added revenue of about USD 72.6 million (FAO, 2018). As of December 2015, the bioeconomy transformation project initiated by the Malaysian government contributed RM 5.97 billion (USD 1.4) to the gross national income, and created RM18.21 billion (USD 4.1) worth of investments, in addition to 23,355 jobs (Arujanan and Singaram, 2018).

6. Current state of bioeconomy in Africa

An analysis by Oguntuase and Adu (2021) on the state of bioeconomy development in Africa revealed that Kenya is ahead of other African countries in terms of people in research and development (R&D). Tunisia is next to Kenya in this category and performed better than South Africa. Mauritania, Lesotho, Liberia, Chad, and Congo are the least performers in this group. With respect to biomass production, Gambia occupies the top spot. Other countries in the top ten are Rwanda, Sierra Leone, Malawi, Democratic Republic of Congo, and

Tanzania. The least performers in this categorization are Algeria, Mauritania, Egypt and Chad. South Africa leads Kenya, Mauritius, Rwanda and Morocco in investments in research and technology. Chad, Lesotho, Liberia, and Congo followed Mauritania in terms of least investment in R&D. African countries performed poorly under the institutional arrangements category. Mauritania, Chad, Lesotho, and Liberia occupied the bottom position in institutional arrangements, production determinants, people in R&D and investment in R&D. In terms of preparedness to adopt the bioeconomy, South Africa, Kenya, Mauritius, Rwanda, and Morocco occupy the top spot. A number of African countries possess abundant biomass resources, but are poorly equipped to adopt the bioeconomy, when compared with countries from Asia, Europe and America. This is primarily attributed to poor government funding of R&D, shortage of technicians and researchers in R&D, inadequate or absence of cutting-edge technologies, lethargic industrial production processes, poor industry-university partnership, and weak institutional arrangements, particularly in the quality of infrastructure and rule of law. Strategies for promoting Africa's bioeconomy must focus on targeted spending to assist R&D initiatives, establishment of an effective innovation system, improved education, and developing markets to boost competitiveness. Increasing foreign investment in the bioeconomy sector will also enhance general governance, infrastructure quality, and the rule of law (Oguntuase and Adu, 2021). Incomplete datasets and nonavailability of comparable data remain major limitations in Africa. In the absence of quality data, it is difficult to formulate good strategies and scale up innovations for sustainable bioeconomy on the continent (Oguntuase and Adu, 2021).

7. Outlook on Nigeria's bioeconomy

According to a recent analysis, Nigeria earned more revenue from non-oil sources in 2016, which amounted to NGN 602.19 billion (53% of total revenue) than it did from oil earnings of NGN 433 billion (47% of total revenue) for the first time since 1971 (Burns and Owen, 2019). Many studies have already identified Nigeria's emerging shift away from oil as its political and economic base, pointing to a swiftly approaching post-oil future. Few recognize, however, that this future has already occurred; Nigeria is and has been in a post-oil era for some years (Burns and Owen, 2019). The implication of this is that, as Nigeria attempts to diversify its economy, it would witness a much lesser dependence on the oil sector and create more employment (Obembe, 2021). As such, a knowledge-driven, and sustainable bioeconomy has a major role to play in this regard.

Considered as a major emerging alternative to fossil fuel resources, biomass can deliver multiple products and energy. As a result, biorefineries are vital to supporting a knowledge-driven and environmentally safe sustainable bioeconomy, which mitigates global warming and climate change (Awasthi et al., 2020). Moreover, biomass carbon sequestration is an imperative net zero-carbon energy resource whose efficient use is crucial to accomplishing many of the SDGs. Biomass could generate an estimated 3000-terawatt hour (TWh) of electricity by the year 2050 and save 1.3 billion tons of CO_2 equivalent emission annually (Antar et al., 2021). With an annual biomass potential of about 200 billion kilogrammes, Nigeria could harness agricultural and forest resources, crop residues, and municipal wastes as a possible feedstock for the sustainable production of bioethanol and biodiesel through integrated biorefineries and microbial conversion for the CBE (Ben-Iwo et al., 2016; Verla et al., 2021; Adeyemi-Kayode et al., 2022). The pyrolysis of wood biomass to produce biochar could create more employment, and serve as a source of income for rural dwellers, owing to high demand as an energy source. The biochar market was worth USD 1.3 billion in 2018 and is expected to reach USD 3.5 billion by 2025. Additionally, the global wood pellet market is anticipated to grow from USD 10.5 billion in 2019 to USD 24 billion in 2025 (Oni et al., 2019). In 2018, Nigeria's palm oil production reached one million tonnes, an amount that was higher than those of other countries around the world, except for Malaysia, Indonesia, Columbia and Thailand (Anyaoha and Zhang, 2022). According to Sadhukhan et al. (2018), one tonne of crude palm oil (CPO) can generate nine tonnes of biomass. Therefore, Nigeria could leverage its oil palm industry as a major supplier of bio-based products to support a sustainable bioeconomy. The blending of palm oil into petroleum-derived diesel could open new opportunities for socio-economic growth in the rural areas. The use of this mid-term option, together with pyrolysis, upgrading to drop-in biofuel and purification of biogas to serve as compressed natural gas, could improve the livelihood of poor populations (Sadhukhan et al., 2018). The estimated worth of Nigeria's food industry was about NGN 1 trillion in 2016 (Ezeudu and Ezeudu, 2019). Given the country's weak power infrastructure, huge amounts of food prepared by these industries cannot be preserved for a long time and as such, must be consumed almost immediately. This suggests that an enormous quantity of food is possibly wasted within this industry, thus generating gigantic organic waste materials that are predominantly disposed of alongside municipal solid waste in many cities (Ezeudu and Ezeudu, 2019). Food waste, lignocellulosic waste, among other organic substrates, have been widely exploited as feedstock for anaerobic digestion as it allows the recovery of value-added products such as new foods, nutrient-rich fertilizer products, in addition to ethanol, methane, hydrogen, and biodiesel production (Banks et al., 2011; Aghbashlo et al., 2019; Tabatabaei et al., 2020; Tsegaye et al., 2021; Ranjbari et al., 2022; Adebowale et al., 2022). Each of the bioprocesses like acidogenesis, methanogenesis and fermentation involved in the biorefinery approach for food waste requires optimization to produce a number of bio-based products in order to expedite transition from a linear economy to a CBE (Ranjbari et al., 2022). However, the challenges of bio-waste valorization centres on the technique, formulating government policies and support for R&D, adoption of high-end technologies to produce products with competitive edge, and the deployment of industrial-scale facilities (Ranjbari et al., 2022).

Whereas, biomass offers enormous opportunities to deliver energy and multiple products (Awasthi et al., 2020), experts have identified problematic issues such as emissions, costs, deforestation and seasonality to be associated with its usage. Biomass fuels from plants, wood and waste contain a substantial proportion of bound nitrogen (Nevena et al., 2021). High amounts of potassium, inorganic sulphides and other inorganic elements have also been reported in some biomass (Wang et al., 2012; Nevena et al., 2021). The transformation and emission of oxides of these constituents, particulate matter and volatile organic compounds lead to various operational problems during biomass conversion processes, thus hindering further deployment as combustion fuels (Sadhukhan et al., 2018; Bamwesigye et al., 2020; Ubando et al., 2021). The operational problems are particularly exacerbated during the combustion of biomass fuels derived from the agricultural sector, contaminated wastes materials and residues from bio-refinery and food processing plants. Furthermore, emissions from biomass combustion have been shown to have deleterious impacts on both the respiratory and cardiovascular systems, as well as cause urban smog and acidification (Sadhukhan et al., 2018; Bamwesigye et al., 2020). A variety of procedures including application of additives, utilization of autotrophic microbes, fuel mixing and leaching out of unwanted components prior to combustion have been demonstrated to be efficient at mitigating the different emission related issues during biomass combustion (Wang et al., 2012; Nevena et al., 2021). The low density of biomass raises the cost of collection, handling, transport and storage along its supply chain (Rentizelas et al., 2009; Nunes et al., 2020). To overcome this problem, processing can be executed at any phase of the supply chain, but prior to transportation, thereby reducing total cost and improving output. More so, densification increases biomass density and eases logistic operations while reducing transport cost and risk of biomass deterioration. Storage is another key stage of the biomass logistic chain. The main risks during this stage remains quality degradation and dry matter losses. An appropriate choice of the storage system, proximity to field/forest and biomass storage period can minimize problems that may arise during this stage. Public storage facilities offer the advantages of reduced cost, financial flexibility and superior expertise in operational and management capabilities (Nunes et al., 2020). The frequent use of biomass in the form of wood fuel, such as firewood or biochar by industries and households could plunge forests into degradation due to felling of trees. While wood and charcoal may drive socio-economic activities, they are also major contributors to deforestation and biodiversity loss (Bamwesigye et al., 2020). Besides, research on the gains of biochar remains significantly arguable, despite its promising potential uses (Ranjbari et al., 2022). Therefore, it becomes crucial to explore alternative sources of energy to dampen the pressure on biodiversity and deforestation, while meeting increasing energy demands due to population growth and urbanization. (Bamwesigye et al., 2020). Agriculture and forest biomass are typified by their seasonality due to weather condition, time of harvest, the need for replanting on the field and afforestation. These lead to considerable seasonal requirement for resources, equipment and workforce, alongside increased cost of obtaining resources. The difficulties introduced by biomass seasonality can be minimized by utilizing multiple feedstocks with different periods of harvest. The application of two different biomass sources, instead of one, can reduce cost by 15% to 20% (Nunes et al., 2020).

The *Bacillus thuringiensis* (*Bt.*) cotton and *Bt.* cowpea recently released for commercialization in Nigeria could contribute excellently to the development of the bioeconomy. Other opportunities include innovation in future foods (such as insects, cultured meat, mycoproteins, chlorella and spirulina) with high dry-matter protein and essential nutrients compared to plant- and animal-based foods. Protein-dense biomass can also be manufactured through direct capture of CO_2 from the air using hydrogen oxidizing microbes and renewable electricity in a closed system, independent of local climate. This technology can achieve a protein yield per unit area that is several orders higher than that of soybean, with about one-tenth of water use. Being a major contributor to Africa's aquaculture production, Nigeria can leverage technological innovations in aquaponics to transform its horticultural sector, enhance sustainable food production and diversify exports using the CBE concepts. Aquaponics is already contributing to the production of fresh, high-quality vegetables and fish protein in Egypt and Kenya (Obirikorang et al., 2021). In Nigeria, indigenous vegetables such as fluted pumpkin (*Telfairia occidentalis*) is primarily exploited for medicine, food, animal fodder and as a potential export commodity. The work of Oladimeji et al. (2020) demonstrated that fluted pumpkin yield in aquaponics system was about five times and eleven times higher than in irrigated and non-irrigated lands, respectively. Additionally, fish production in the aquaponics system was 75% and 29% more efficient than static aquaculture and recirculatory systems, respectively. Nigeria's abundant wood (lignocellulosic) biomass offers new prospects for the sustainable production of next-generation of high-performance bioplastics (Xia et al., 2021; Chen et al., 2022), wood-plastic composites (https://www.ri.se/en/what-we-do/expertises/wood-based-materials-and-products), wood-derived polyphenols and hydrogels for targeted and controlled drug-delivery platforms (Stevanovic et al., 2009; Culebras et al., 2021).

8. Direction for future research

It is crucial to develop and deploy sustainable biomass production methods to allow the establishment of a flourishing bioeconomy (Antar et al., 2021). An in-depth investigation of a wide range of crop plants to unravel metabolic pathways that underpins biomass accumulation using diverse 'omics' technologies could enhance our current vis-à-vis regarding their production and utilization within the context of the bioeconomy (Antar et al., 2021). Energy generation in the foreseeable future, will require enormous amounts of biomass (Antar et al., 2021). Consequently, modern genetic techniques would be required to select and develop new crops, or new varieties of existing crops that can cope on marginal lands or even wastelands, while optimizing biomass yield (Bosch and Hazen, 2013). Attempts should be made, under field conditions, to select crops that generate maximum quantity of biomass for biofuel commercialization (Antar et al., 2021). To improve biomass yield in the residues of food crops or in biomass crops at the level needed to sustain a bioeconomy, gene or gene clusters that mediate specific metabolic pathways involved in the production of biomass could be modulated to allow efficient allocation of soil resources, enhanced level of photosynthetic activity and alteration of plant canopy structure to improve fluence interception. In this regard, the CRISPR-Cas9 (Clustered Regularly Interspaced Short Palindromic Repeats-CRISPR-associated protein 9) gene editing technology has gained tremendous popularity due its ease of deployment and economic consideration as a low-cost technique (Prasetya and Nugroho, 2021). Through the over-expression of the TaEDR1 gene, the CRISPR-Cas9 technology was used produce rice resistant to powdery mildew, thus leading to improved yield and quality (Zhang et al., 2017). The successful application of the system to improve genetic traits in several food crops including rice, Brassica species, sorghum, maize and wheat, shows promise for cross-application to improve biomass production (Zhang et al., 2017; Prasetya and Nugroho, 2021) in energy crops like Jatropha, which is abundant in Nigeria. Modifying the expression of target gene(s) that control the uptake, assimilation and transport of phosphorus and nitrogen is a feasible approach to enhance their use efficiency for sustainable food production and biomass (Cao et al., 2017; Jaganathan et al., 2018). The CRISPR-Cas9 system could also be coupled with tissue culture techniques via transformation and regeneration. The abundant microbial community associated with plants known as the plant microbiome can significantly boost plant growth and enhance biomass accumulation (Arif et al., 2020). Most plant-microbiome research has been directed towards enhancing yield and disease resistance in food crops, with rare consideration for energy crops (Antar et al., 2021). Exploitation of the phtyomicrobiome represents a promising strategy to stimulate plant growth and development through direct and indirect mechanisms that leads to biomass accumulation, particularly under unfavourable conditions. For instance, microbiome modulation via inoculation with a consortium of plant growth-promoting rhizobacteria (PGPR) can enhance plant biomass yield, plant development and mitigate abiotic stresses. Manipulating the plant holobiont (symbiotic microbial communities that cooperatively exist internally in plants (endosphere), on leaves (phyllosphere) and externally on roots (rhizosphere)) via microbiome engineering is a potential biotechnological approach to improve yield and resilience in energy crops. Microbes and microbial enzymes better suited for biomass conversion can be developed and applied to genetically modify biomass crops to reduce energy and economic costs associated with processing and production (Antar et al., 2021). With the promotion of resource recovery, more attention should be directed towards improving the economic viability, cost effectiveness, control process stability, foaming control and buffer capacity of biorefinery technologies for the production of energy from biomass and organic waste (Ranjbari et al., 2022).

Conclusion and recommendations

Considering that biotechnology plays a key role in contributing to the modern bioeconomy, the recommendations highlighted by Obembe (2010) in our opinion are still relevant to the establishment of a Nigerian bioeconomy. These include: (i) aggressive and deliberate awareness strategies concerning biotechnology vis-à-vis the potential benefits in the context of a bioeconomy; (ii) revisiting policy framework for education in Nigeria to trigger young people's interest in science and technology at the primary secondary levels. More so, there is need to redesign curricula at the tertiary level to incorporate biotechnology courses as an essential component. This aligns with other perspectives that the manpower development for the nation's bioeconomy sector should not be through workshop and seminars, but long term trainings (iii) establishment of infrastructures for low- and high-end techniques such as genome editing, tissue culture, and genome sequencing, as well as analyses for the Universities, while increasing funding for bioeconomy research, development, and innovation (R&D/I); (iv) basic and applied research on key enabling technologies, as well as strengthening links between science and business through interdisciplinary co-operation between universities, research institutes, and industries should be encouraged; (v) making available, motivation and incentives, with a view to retaining highly skilled manpower and to make overseas-trained human resources return home. Transition to a bioeconomy requires well-trained workers with specific knowledge, skills and competencies needed for the sustainable utilization of bio-based resources in consumer production and manufacturing. This will require establishing centres of excellence, multidisciplinary approaches that highlights systems thinking, tactical planning and assessing socio-economic, environmental performance, and a knowledge of current technologies and local specifics (El-Chichakli et al., 2016); (vi) massive investment in broadband information technology infrastructure, which is critical to enhancing knowledge transfer and applications; (vii) establishment of specialized biotechnology centres of excellence in order to ensure capacity building in priority areas; (viii) establishment of collaborative technology park/ventures/incubators with the private sector to ensure that biotech products reach the market; (ix) fostering of international linkages and partnership, and attraction of foreign investments, all of which can only be achieved when functional basic facilities are existent; (x) establishment and consolidation of existing regulatory, biosafety and intellectual property bodies to map out more effective biotechnology guidelines and policies, in addition to setting up certification and testing facilities; and (xi) investments in infrastructure critical to the bioeconomy e.g., potable water, reliable power supply, roads, biomass storage and processing facilities. There is need for the government to expedite and finalize the process of setting up a defined and coherent national bioeconomy strategic policy that can maximally harness biotechnology to develop Nigeria's CBE (Obembe, 2021).

Finally, while the bioeconomy is eliciting heightened attention as an avenue to tackle climate change, reduce fossil fuel dependence, attain food sovereignty and increase the industrial application of biomass resources, it is noteworthy that a few negative impacts could arise with its development (O'Brien et al., 2017; Priefer et al., 2017). The largescale production of biomass feed stocks (from food crops like maize, soybean and sugarcane) to meet the demands of the bioeconomy could exacerbate the risk of land grabs/expropriations, leading to land use change and conflicts, and marginalization of local farmers who recognize the economic prospects in growing biofuel crops (Perišić et al., 2022). The direct effects of land use change include increased GHG emissions (which contributes to climate change) due to the clearing of forests for new production sites, energy utilization during the processing of biomass and application of divergent planting methods. Although marginal lands have been proposed by experts for biomass production within the bioeconomy, their use can lead to loss of biodiversity that are critical for ecosystem function (Pfau et al., 2014; Issa et al., 2019). Other problems identified include detrimental ecological effects such as eutrophication and pests associated with novel crops that may infest neighbouring ecosystems, as well as transnational exploitation of natural resources and its regionally differentiated social and ecological effects as we have seen with the case of crude oil in the Niger-delta region of Nigeria (Pfau et al., 2014). To avoid or minimize these problems, the development and implementation of stringent bioeconomy policies and laws that encompasses eco-socio-economic dimensions as an input for regulation by legislators, researchers and corporate actors is imperative (Gawel et al., 2019; Vogelpohl, 2021; Perišić et al., 2022). For instance, GHG emissions can be substantially reduced by implementing an effective carbon policy that makes defaulting industries pay for the related environmental issues, while proposing incentives for corporations that adopt business models that support energy policies and innovative renewable products (Issa et al., 2019). The time has come for Nigeria to develop its own indigenous technologies for biomass conversion and biofuel production from its abundant lignocellulosic resources. Huge investments into biomass storage and logistics facilities are also needed. It may be required to raise awareness about the relevance of biofuels, and promote an appropriate business climate for domestic and foreign investors (Adewuyi, 2020). Nigeria must establish her own bioeconomic agenda to suit its unique circumstances, capacities and requirements, while recognizing possibilities and involving key players in her many sectors (Obembe, 2021).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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