The role of information technologies in developing innovative bioeconomic ecosystems for sustainable transformation

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Abstract

A prerequisite for overcoming the modern challenges that arose at the beginning of the 21st century is the transformation of production and consumption systems per the principles of sustainable development. The most promising approaches in this transformation are the convergence of the knowledge-based bioeconomy and digitalization, which will contribute to developing an innovative circular bioeconomy. Innovations play a crucial role in the dynamics of the bioeconomic transformation by generating gross added value, increasing profitability and labor productivity, and enabling the adoption of modern technologies. The primary driving force for changes in business activity is usually the search for a niche that provides a competitive advantage for enterprises. This advantage can be achieved by creating new value chains or modifying the configuration of existing ones in the bioeconomy, all within the framework of sustainable development. This article aims to determine the role of information technologies and trends in developing innovative activities in Ukraine's bioeconomy sector. This determination is based on a comparative statistical assessment of key indicators of business entities that can be attributed to the innovative bioeconomy. The analysis reveals that the share of innovative products in the volume of industrial products sold in Ukraine averages at 1.9%, significantly lower than European countries' indicators. The low level of innovativeness in Ukraine's bioeconomic sector is a direct consequence of the limited investment in innovation, which decreased by almost 70% between 2014 and 2020. It has been revealed that the structure of innovative products within the bioeconomic sector is primarily dominated by enterprises utilizing medium and low-tech production processes, such as food, chemical, and woodworking industries. On the other hand, high-tech production includes the manufacturing of primary pharmaceutical products, pharmaceutical preparations, computers, electronic and optical products, which is mainly represented by enterprises within the traditional sector that heavily rely on fossil resources. Research indicates that the level of technological advancement and innovation in the Ukrainian bioeconomic sector is currently low and exhibits a negative trend. Although enterprises operating in the bioeconomic sphere possess significant potential for development and innovation implementation, their production, operational, and economic processes require reorganization and modernization by integrating innovative approaches.According to the author's vision the conceptual model of bioeconomic digital transformation based on sustainable development, delivered in the article, integrating modern information technologies, into the bioeconomic transformation process can facilitate the creation of a unique digital environment called innovative bioeconomic ecosystems. These ecosystems aim to support the sustainable bioeconomic transformation of socio-economic systems by engaging all relevant stakeholders. By adopting the proposed approach of digital transformation within the bioeconomy, it becomes feasible to achieve the primary objectives of sustainable development, including the creation of new employment opportunities, enhanced competitiveness of bioeconomic products, improved quality of ecosystem services, promotion of consumer-oriented production, resource conservation, and climate impact.

Keywords

Bioeconomic ecosystems, management, digitalization, innovations, industry

1. Introduction

In recent years, the concept of bioeconomic transformation has gained momentum and has been incorporated into numerous national and international economic strategies as a promising solution

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for addressing the challenges of sustainable development, such as climate change, depletion of natural resources, and the disappearance of ecosystems. The primary objective of bioeconomic transformations is to reduce dependence on fossil resources by introducing new bioproducts, processes, and methods [1]. Additionally, they aim to foster the development of bio-oriented socio-economic systems based on knowledge [2], while creating opportunities for "green growth" [3].

Research often highlights the potential of the bioeconomy in rural areas, where agriculture plays a dominant role in the employment structure [3, 4]. However, applying bioeconomic knowledge and biotechnologies is equally crucial in industrial sectors, particularly in processing industries that employ innovative technological solutions. The bioeconomy is a multidisciplinary field that combines knowledge and expertise from various sectors. It opens up new technological possibilities in engineering, information technology, robotics, machine tool construction, energy, packaging, pharmaceutical industries, and more [1].

The modern bioeconomy aims to utilize biological resources efficiently, demonstrating economic and innovative practices, making it relevant even for large industrial cities. Furthermore, its significance is increasing in terms of knowledge generation, as well as the establishment of innovative networks and databases. A contemporary interpretation of the bioeconomy revolves around the production, exploitation, and utilization of biological resources, processes, and systems in all sectors of the economy, aligning with the principles of sustainable development [2]. Some researchers call this concept a knowledge-based bioeconomy because it emphasizes new technologies and processes [5].

Previous bioeconomy strategies have emphasized its crucial role in the sustainable development of rural areas, as establishing local production facilities near the sources of biomass, the raw material, contributes to their economic growth. By creating local value chains, the financial appeal of these regions, including attracting skilled labor, is enhanced [2, 6]. While the potential of rural areas in bioeconomic transformation is undeniable, the role of urban regions in the bioeconomy is often underestimated. It requires discussion in the context of supporting innovation and circularity.

In the contemporary context of the bioeconomic transformation of socio-economic systems between rural and urban areas, there is a clear need for complementarity and the exploration of the potential for mutual exchange of skills among a wide range of stakeholders. The establishment and advancement of shared bioeconomic ecosystems, characterized by unhindered access and information sharing among stakeholders at different levels, can ultimately lead to interdisciplinary innovation through research conducted by both corporate and academic entities and their practical implementation.

To achieve the necessary innovative solutions for bioeconomic transformation, it is imperative for various stakeholders from all system levels – including the scientific community and the business environment – to collaborate [7]. Generating new knowledge and adapting existing approaches to new directions often serve as the foundation for innovation [8]. Information technologies occupy a significant role in this process, with research digital networks playing an essential part in facilitating access to and exchange of information and experiences, thus fostering the generation of novel ideas. This, in turn, enhances the competitiveness of companies, sectors, and entire regions [9].

Within the bioeconomic ecosystem, the connections established between industry and scientists are particularly crucial during the early stages of the innovation process, as they facilitate the integration of research findings into the real sector of the economy.

The adoption of an innovative state policy should establish prerequisites to support scientific cooperation in the development of innovations in the bioeconomy by introducing appropriate financial mechanisms. Scientists at The Swedish Foundation for Strategic Environmental Research [10] believe that the entire bioeconomy business cycle is ready for digitization. This encompasses the extraction and procurement of raw materials [11], bioprocessing, logistics and distribution of intermediate goods. Information technologies are already prevalent in various aspects of the bioeconomy, including the digitization and tracking of existing biological resources [12], information protection [13], the development of new bioproducts in bioengineering [14, 15] and biochemistry [16], conducting relevant tests [17], as well as the implementation of innovative production methods such as biofoundries [18], bio-based three-dimensional (3D) printing [19], and cell-free synthetic biology [11]. Additionally, it is crucial to consider the retail trade of final products for consumers, focusing on the principles of circularity and sustainability in the bioeconomy, encompassing the reuse, repair, and processing of products and materials.

One of the most significant benefits of digitalization is the ability of ICT to bring bioeconomy ecosystems to a wider audience. Even two decades ago, to spread innovative approaches in the economy, government representatives had to make a series of demonstration visits, organizing a significant number of events to inform and demonstrate the benefits of innovative approaches to industry and the general public. This process was time-consuming, and the audience reached was limited to the physical size of the room and then spread by word of mouth.

Creating digital bioinnovation ecosystems can work on several levels. Firstly, the reach of the audience increases significantly. Secondly, such e-ecosystems can serve not only to disseminate information about available grants, vacancies, events, and contracts but also to create entire research databases that can be utilized for both research and commercial purposes. This approach is not dependent on geography and can be applied both at the international and institutional levels, providing advantages and possibilities that warrant further research.

2. Evaluation of innovative activities in Ukraine's bioeconomic sector

Traditionally, the majority of innovations have been produced in the processing industry. In Ukraine, the processing industry accounts for the largest number of innovatively active enterprises, making up about 22%. The highest share of enterprises with technological innovations is also found in the processing industry, with over 15%, as well as in the supply of electricity, gas, steam, and air conditioning, with over 12%. Furthermore, processing industry enterprises contribute to over 15% of non-technological innovations. However, it is unfortunate that the level of innovativeness in the Ukrainian industry, and consequently the overall economy, is the lowest in Europe. In 2020, the share of innovative products, referred to as product innovation, in the volume of sold industrial products in Ukraine was only 1.9%, while in Poland, this value exceeded 9% [20].

Among the enterprises in the processing industry, those in the traditional sector, primarily dependent on fossil resources, such as mechanical engineering, printing, and metallurgy, possess the highest level of innovation [21, 22]. On the other hand, the low-tech production sector, including the food, light, woodworking, and furniture industries, which predominantly belong to the bioeconomy (figure 1), exhibits the most minor innovation.

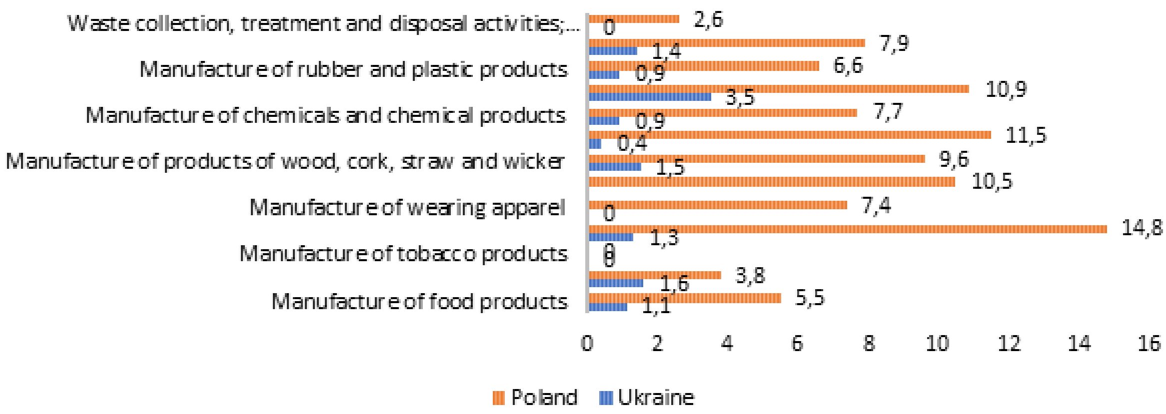

Figure 1: The share of innovative products in the volume of sold products (goods, services) of bioeconomy enterprises of Ukraine and Poland, 2020, in %.

The technological level of industrial production is closely correlated with the level of product innovation (figure 2).

As can be seen from figure 2, in Ukraine, the share of innovative enterprises in the bioeconomic sector that use low- and medium-low-level technologies is predominant and remains relatively unchanged over the years. However, a slight increase in the number of enterprises that use medium-high-level

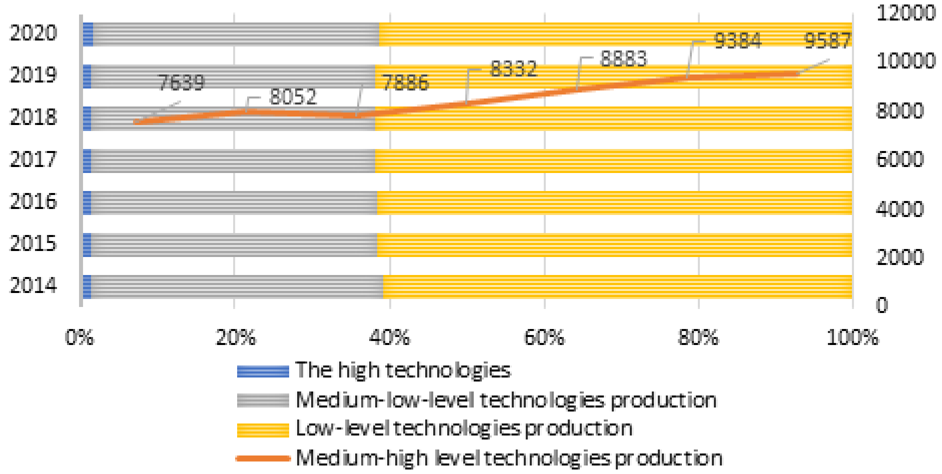

Figure 2: Structure of innovation enterprises in bioeconomic sectors of Ukraine, by levels of technology in 2020.

technologies can be noted starting from 2019.

High-tech manufacturing encompasses basic pharmaceutical products, pharmaceuticals, computers, and electronic and optical products. Overall, the low level of innovativeness and technology in the Ukrainian bioeconomy is one of the key reasons for the high import dependence of the national economy on products of intermediate and final consumption from high- and medium-high-tech industries. These industries primarily include machine-building, textile, chemical, and pharmaceutical sectors [23, 24].

The generally low level of innovativeness of industrial products in Ukraine and the bioeconomic sector is a direct consequence of the low level of investment in innovation. The volume of investment in innovation decreased by more than 70% from 2012 to 2020 [25]. In the bioeconomy sector, the largest decrease in costs for innovative activities during 2018-2020 (figure 3) is observed in the field of leather, leather products, and other materials production (-80%) and furniture production (-59%). However, costs for innovative activities in the food, beverage, clothing, and pharmaceutical production sector increased on average by more than 200%.

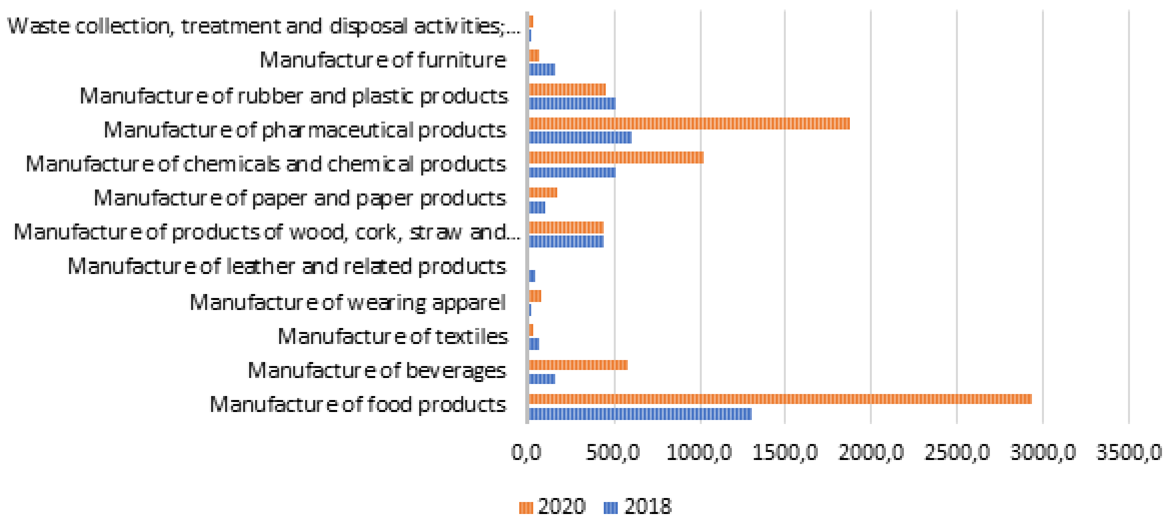

Figure 3: Dynamics of costs of innovation in the bioeconomic sector of Ukraine in 2018-2020, UAH million.

At the same time, in the information technology sector (figure 4), which indirectly contributes to the development of the innovative bioeconomy through the digitization and automation of processes, there is a significant increase in spending on innovative activities in the field of computer programming (+70%). However, there is only a three percent increase in engineering and technical testing.

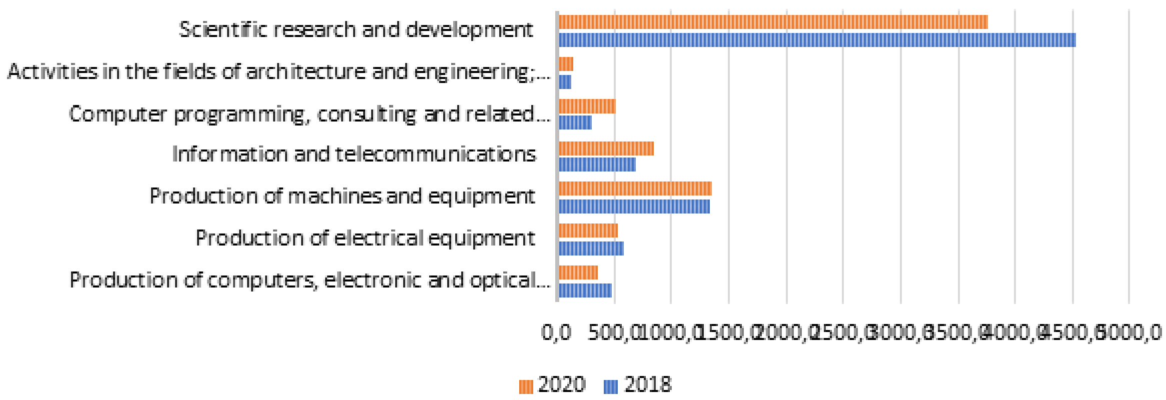

Figure 4: Dynamics of innovation costs in the information technology sector of Ukraine in 2018-2020, UAH million.

3. Conceptual vision of the need to develop innovative bioeconomy ecosystems

Despite the fact that, as a rule, large companies invest in research and development (R&D) in international practice, recent scientific opinion [26] indicates that the situation is changing. New players and innovators, rather than mature companies, are leading in bioeconomic research and development. This can be partly explained by the fact that these enterprises start with a specific goal in mind – the creation of bioeconomic value. As a result, radical innovation becomes the core of their business rather than just an experimental risk on the side, allowing them to focus on transformational activities.

The development of a bioeconomic strategy that can stimulate a high level of bioeconomic entrepreneurship will not only enable a rapid transition to a bioeconomic model but also bring about positive indirect effects, such as creating additional jobs through startups. This will benefit overall economic development. To activate entrepreneurial, innovative activity, it is necessary to create prerequisites and potential opportunities for entrepreneurial initiatives, which can stem from the bioeconomic transformation.

Such entrepreneurial initiatives carry a relatively high risk inherent in the bioeconomy [27]. The high level of risk in bioeconomy entrepreneurship arises from the need to compete with mature and efficient markets dominated by companies that still create value using fossil resources. Consequently, limited data and information about market conditions, such as consumer acceptance of new bioproducts, increase the risk level in entrepreneurial activities, making them less attractive to large corporations. This problem can be addressed through entrepreneurs' distinct approach to innovation management, which significantly differs from how large corporations implement their innovation projects. Some scientists call this approach an "entrepreneurial experiment" [28, 29]. By swiftly testing new technologies, developing applications, and creating new products based on these technologies, entrepreneurs can mitigate risks and uncertainties regarding the viability of their inventions. They can quickly obtain feedback after testing the product in the market, thus attracting consumers at an early stage. Rapid prototyping and testing can have a similar effect by reducing risk and cost. Entrepreneurial activity can be likened to scientific activity [30], focusing on verifying business models rather than generating new scientific knowledge. Consequently, developing innovative business models in the bioeconomy becomes a primary task of entrepreneurial activity that exceeds the capabilities of other interested parties. The process of bioeconomic transformation has the potential to not only replace key fossil resources with biological ones but also introduce entirely new methods of generating added value [31].

Entrepreneurship is indeed significantly impacted by the transition to the bioeconomy at the micro level. This transition involves converting bioeconomic opportunities into innovative biotechnological business models through experiential learning processes. However, not all entrepreneurial individuals possess the necessary technological and organizational expertise to effectively market their bioproducts or scale up bio-innovations in the market. Additionally, entrepreneurial initiatives in the bioeconomy often face substantial financial challenges. For instance, establishing a biorefinery necessitates significant investments, which can hinder potential entrepreneurial ventures. These limitations highlight the importance of establishing a regional institutional environment that fosters governance and supports aspiring entrepreneurs.

The mere intensification of individual entrepreneurial activity is insufficient to ensure the bioeconomic transformation of socio-economic systems. The environment in which entrepreneurial activity occurs represents a crucial aspect of the researched issue. To obtain a comprehensive understanding, it is essential to focus on entrepreneurship and enterprises as grassroots socio-economic systems and their innovative infrastructure. At the regional level, or the meso-level of the economy, the main institutional environment determines the potential for realizing innovative bioeconomic opportunities in specific market conditions. Therefore, foreign scientific literature on the bioeconomy emphasizes the role of centers, clusters, or innovative (eco)systems [32] – dynamic bioeconomic systems that collaboratively implement bioeconomic innovations.

As this study concentrates on the role of information technologies in the development of innovative bioeconomic ecosystems, it is appropriate to define a bioeconomic ecosystem. Such ecosystems can be understood as regional, complex agglomerations of bioeconomic activities that offer formal and informal support services for bio-innovative entrepreneurship. These ecosystems benefit the broader economic and social environment and enhance the prospects of success for bioeconomic transformation at all levels. In essence, bioeconomic ecosystems act as catalysts for the impact of bio-innovative entrepreneurship on bioeconomic transformation. They contribute to entrepreneurship in the bioeconomy by increasing flexibility [33], facilitating the transfer of knowledge and technologies, and creating value networks among various participants [34]. They are an important element of the overall transformation. To function effectively, bioeconomy ecosystems must include diverse stakeholders and institutions, providing innovative entrepreneurs with interdisciplinary skills, knowledge, and experience. The functioning of the bioeconomic ecosystem attracts entrepreneurs and investors to a particular region because it creates a positive image of innovation and market potential, which contributes to future transformative processes. Such ecosystems are not externally controlled; they are mostly self-regulating [35] and driven by a culture of innovative entrepreneurship characterized by creativity, openness, innovation, and a positive attitude toward risk. Thus, the creation of bioeconomic ecosystems reduces barriers for entrepreneurs and enables them to develop innovative ideas more easily.

Understanding that regional agglomerations, or bioeconomic ecosystems, can facilitate bioeconomic transformation raises the question of whether such entrepreneurial ecosystems emerge spontaneously or must be deliberately created. Quite often, such entrepreneurial ecosystems develop due to the activities of universities [36] or research centers. Kircher et al. [37] state that market demand for bio-products can also contribute to creating a bioeconomic ecosystem. Often, the less formal exchange of knowledge, typical in entrepreneurial activity, can have more significant potential than direct collaboration with academic institutions. The dissemination of knowledge among the elements of the bioeconomic ecosystem requires entrepreneurs to be close to other entrepreneurs and participants, such as scientists, politicians, producers, and end consumers. The greater the number of participants and diverse stakeholders involved in the ecosystem, the more comprehensive the range of knowledge available [38], which is crucial for the bioeconomic transformation process.

4. Assessment of the development of the information technology sector in Ukraine

The knowledge-based bioeconomy and digitalization are two promising technological approaches that need to be considered together to contribute to the transformation and trigger the necessary technological dynamics. However, such a broad transformational process requires the participation of all stakeholders in society. Innovative bioeconomic ecosystems can become centers for the formation of future policy projects supporting bioeconomic transformation, but further research into the potential of using digital solutions and highly qualified personnel is needed. The transition to innovative bioeconomic development based on information and leading information technologies is particularly relevant for preserving the integrity and independence of Ukraine, restoring its industrial potential, and transitioning to sustainable development. For this purpose, information technologies should be laid as a basis for the preservation at this stage and the subsequent revival of all components of the economy of the regions, which will become a condition for the reconstruction of the country in the post-war period.

The information technology sector in Ukraine is at the stage of formation and development, as evidenced by the dynamics of the growth of the information technology market in recent years (figure 5)

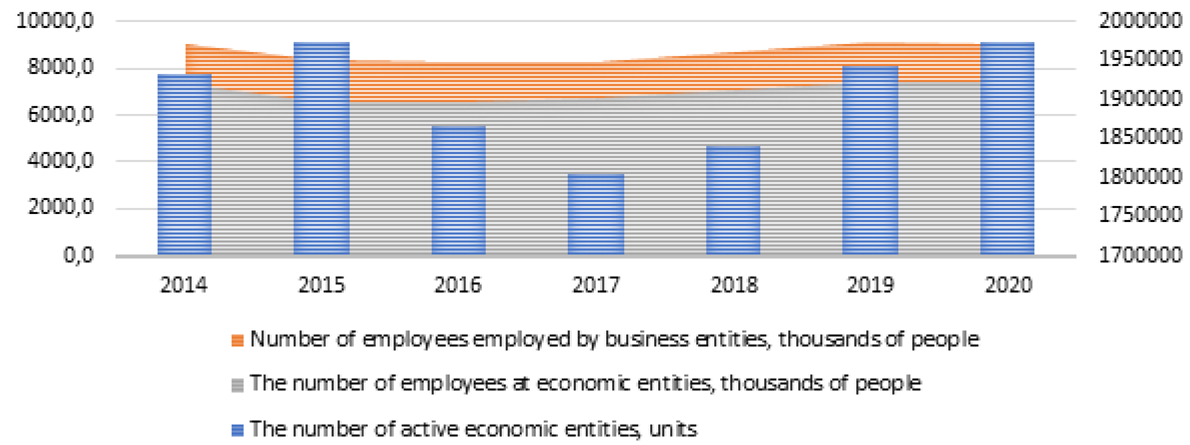

Figure 5: The dynamics of the development of the information technology market in Ukraine 2014-2020.

Unfortunately, despite the significant human potential, the information technology market is constantly undergoing changes, particularly in light of recent economic and political events in Ukraine. The aggression of the Russian Federation in 2014 has led to the outflow of enterprises and IT specialists abroad. However, despite these challenges, the IT sector has shown positive growth trends, as evidenced by the dynamics of the results of IT sector enterprises (figure 6).

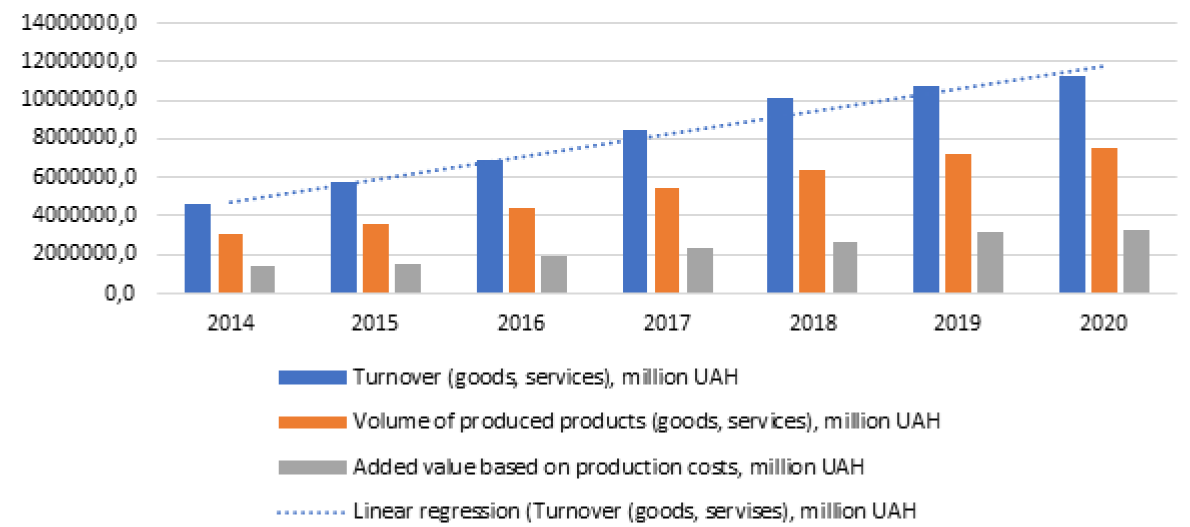

Figure 6: Dynamics of the results of the activities of enterprises in the information technology sector from 2014 to 2020

5. Analysis of the role of information technologies in the development of bio-innovative ecosystems

Conducting biotechnological and bioeconomic experiments has historically been challenging due to the scarcity of data. However, in the 21st century, the situation has undergone a significant transformation.

Developing technologies in high-performance experimental measurements has facilitated the creation of large data sets associated with biomaterials. Consequently, the need arose to develop tools that simplify the analysis and interpretation of biological data [39]. Table 1 provides a systematic overview of the role of digital technologies in bio-innovative development.

Table 1
Overview of IT contribution to the development of bio-innovative ecosystems.

Field	Problem	Possible solution
Integration of biotechnology with the engineering design cycle	In the engineering design cycle, the test phase, or testing, is the biggest problem.	The task of conducting successful tests in engineering design can be solved with the help of biology and the automation of iterative processes [40]
	Most biotechnologies still need to meet specific criteria of bioengineering today, primarily due to the significant differences between the scientific method and an engineering project.	Creating integrated engineering design technology platforms with biotechnology can unlock the commercial potential of scientific developments, especially when combined with digitization and automation. The data sets generated through this process can be embedded in machine learning models, which have the potential to reduce human involvement in the design-build-test cycle [14].
	Reproducibility is a persistent problem in research, the essence of which is that design tools for process research and development (R&D) are inadequate.	The emergence of global supply chains requires coordination through blockchain technology. Further development will lead to an increase in the portfolio of products and information. What accompanies it, especially considering the need to consider the cost minimization principle and regulatory pressure. Therefore, software integration should go far beyond integration in laboratory conditions [15].
	Experimental high-throughput measurements produce large amounts of data that are difficult to process and store.	Overcoming testing bottlenecks requires implementing new evaluation methods for high-throughput measurements and applying sophisticated metrology approaches. These approaches often involve bioimaging techniques and information workflows that are typically automated and reliant on complex software. The software's task is to collect and manage both qualitative and quantitative data [17]. Process automation enables reliability, predictability, and reproducibility when scaling up laboratory studies and implementing them in production.
	Reliability and predictability are two other aspects that affect reproducibility.	Creation of new specialized bioengineering programming languages (Antha) to solve the problem of reproducibility. It is claimed that Antha allows conducting experiments of an entirely new level of complexity. It can provide a departure from experimentation, changing one factor at a time, fixed in the scientific method, by identifying the interaction between many different experimental factors [41].

Subsidies for R&D aimed at achieving the reproducibility of bioproduction processes. Pre-competitive design of R&D programs (for the level of laboratory research) and programs for adaptation to market conditions can guarantee the success of research only if it can be reproduced and utilized in the real economy sector. Market research is also an equally important issue, including the reliability of designs, titers, yield, and productivity under the influence of various variables on bioprocesses, such as changing environmental conditions, internal gradients like oxygen and redox, and resistance to cell destruction, among others. The combination of digital and biological tools represents the most effective way to reduce the time required to confirm the accuracy of research results, considering the complexity of biological processes.

In addition, it is important at the state level to ensure support for the necessary platform technologies that underpin the bioeconomy ecosystem (e.g., biofoundry, distributed research and development networks, digital platforms, data control, and digital/genetic data storage). Such support can only be provided at the state level because the investment risks for the private sector are too high, which hinders the development of innovations and their competitiveness in the market. Subsidizing research and development alone is not sufficient in such a situation; innovative forms of public-private partnership need to be developed. This form of cooperation will allow both public and private entities to have equitable access to equipment and services while ensuring data security and intellectual property protection. Table 2 presents the contribution of information technologies to the development of green biotechnology, security, and data storage.

Table 2
Overview of IT contribution to the development of green biotechnology, security and data storage.

Field	Problem	Possible solution
Convergence of industrial biotechnology and green chemistry	The main problem that prevents the mass production of bioequivalent chemical substances is their low competitiveness compared to traditional raw materials. Three critical indicators of bioprocesses are often worse than in petrochemicals: titer, yield and productivity. These rates are often too low to scale because most natural microbial processes are incompatible with an industrial process [42].	Combining industrial biotechnology approaches with green chemistry and information technology/computing can solve these problematic issues. There are many opportunities for digitization to enhance the manufacturing benefits of combining industrial biotechnology and environmental chemistry. For example, [16] proposed automated molecular design (CAMD) for bio-based product molecules.
Data analysis and storage	Overcoming the problems of the testing and convergence phase leads to new challenges and obstacles in the analysis and storage of data due to their excessive amount. In the next two decades, a data storage crisis is brewing, as silicon-based storage methods cannot keep up with demand.	DNA as a storage medium may offer a way to avert the storage crisis. It seems that this is not real, but it is already possible to translate digital information into genetic information [43]. DNA storage is too expensive as a storage medium because the technology is still in its infancy.
Blockchain to share benefits and protect confidential information	The globalization of markets will require new architectures, algorithms and software to improve quality, efficiency and cost-effectiveness, as well as data analysis, visualization and sharing of big data. Cyber security is also problematic in the biological industry, which produces biochemical substances and materials.	Blockchain, which uses highly secure distributed database technology, has many advantages for different types of scientific projects and companies. Blockchain is well suited for managing areas such as supply chain, privacy, transaction processing, contracts and licensing, as well as confidential medical records and enforcement of intellectual property rights [11].
Digital security	Biomanufacturing relies heavily on data, intellectual property and research that needs to be protected so that companies can reap financial benefits from their investments.	Many different types of organizations are involved in biosafety. They range from raw material suppliers and customers to information technology (IT) professionals from law firms and offices. Cyber security is only as strong as its weakest link in the overall defence system [13]. Unfortunately, the pace of defence development has lagged behind their willingness to use digital technologies to drive innovation, and there are many ways to launch a cyberattack against a biotech company today.
Cloud computing	The need to optimize complex biotechnological processes in order to reduce business costs.	Cloud solutions can make data available for different levels of testing while meeting security and regulatory requirements. In addition, the cloud provides comprehensive analysis of data from the Internet of Things and devices in real time [13].

The widespread adoption of digital technologies necessitates the development of standardization and interoperability policies, drawing parallels to the experiences of the microprocessor industry. A similar approach is also observed in the field of engineering biology, although the contemporary context emphasizes certain differences. Specifically, the issues of open access, information protection, and intellectual property rights must be carefully addressed to meet the requirements of academia and adequately incentivize private investment.

The matter of standardization, ensuring compatibility among products and processes, also holds significant importance for legal settlements. Regulatory frameworks may mandate licenses to be either royalty-free or royalty-free under terms that are considered "fair, reasonable, and non-discriminatory", a system widely employed in the ICT sector [44]. Furthermore, it is crucial to establish regulations governing user access to proprietary and standardized databases or inventions. Table 3 presents the overview of IT contributions to the development of bioeconomy frontiers.

Table 3
Overview of IT contributions to the development of bioeconomy frontiers.

Field	Problem	Possible solution
Frontiers of bioproduction	Information technology supports future promising bioproduction strategies: biofoundries, bio-based three-dimensional (3D) printing and cell-free synthetic biology.	Bifoundries can integrate tools, technologies, and general process analysis into a platform to enable more efficient biological engineering. By shortening the cycle time and increasing capacity, biofoundries can help achieve sustainable development goals [18]. 3D bioprinting uses the layer-by-layer precise placement of biological materials, biochemical substances, and living cells [19] with special equipment to produce 3D structures. Currently, the most relevant application of cell-free synthetic biology concerns metabolic engineering for producing fuels, chemicals, and materials [19].
Skills and education for the bioeconomy workforce	The crux of the problem is the need for much more interdisciplinary education.	Educational training of specialists should combine biology and engineering fields. It is necessary to review the role of mechatronics in forming educational programs for training future specialists in bioengineering. Competencies that combine a mechatronic engineer relate to mechanics, electronics and information technology, which can be used to create simpler, more economical and more reliable systems [45].
Digitization of biological resources	Managing complex systems requires IT tools such as applications, websites, consumer platforms and databases. In addition, it is often necessary to use them in an integrated manner to manage demand and extend their influence throughout the value chain.	The ecosystem of local bioprocessing industries and value chains can include hundreds of thousands of bioresource owners, entrepreneurs and companies specializing in service, procurement, transport and logistics, as well as the production of bioproducts or energy. Digitization can offer solutions for bioresource industries that will add value to the bioeconomy [10].
Satellite technologies	Satellite technologies can be a critical tool for the bioeconomy, monitoring biodiversity and combating illegal extraction of biological resources.	Satellite technologies enable the national bioresource monitoring system to collect and provide economically efficient and controlled, high-quality information on the three pillars of the bioeconomy (social, economic and environmental) [12].

According to table 3, the main problematic issues that information technologies can solve for the further development of the bioeconomy are the introduction of new production technologies with the help of 3D printing, biolaboratories, and cell-free synthetic biology. Additionally, satellite technologies and the digitalization of existing bioresources for further use and tracking can ensure clear monitoring of bioresources [46]. However, it is important to note that the issue of highly qualified interdisciplinary specialists is the most crucial aspect to address. While there are many specialists with various profiles, there is a shortage of individuals with a combination of knowledge from different areas. To address this, it is necessary to prioritize interdisciplinarity in educational programs at the political level. These programs should focus on bringing engineering biology into contact with other disciplines, such as materials science, automation, chemistry, informatics, and engineering. Both chemistry and biology can benefit from higher levels of digitization, and there should be a particular emphasis on fostering synergy between engineering biology and environmental chemistry.

Questions related to the digitalization of the economy have emerged within the framework of the fourth industrial revolution. This concept encompasses processes involving the implementation of cybernetic systems, utilization of the Internet of Things (IoT) [47] and related services [48, 49], as well as direct online communication between individuals and machines. The bioeconomy amalgamates two pivotal forces of the modern industrial revolution: shifts in socio-economic structures, environmental considerations, decarbonization, enhanced resource utilization efficiency, and a focus on decentralization, particularly on small and medium-sized enterprises. Consequently, this shift necessitates greater technological and innovative solutions, accompanied by a simultaneous escalation in automation and digitization. Innovative bioeconomic transformation is underpinned by the increasing integration of dynamic supply chains and the interplay between diverse industries and sectors. Given that the bioeconomic transformation context encourages thinking in terms of an ecosystem, often encompassing a multitude of business partners in the supply chain, the key prerequisite for its proper functioning becomes transparency and comprehensive information provision within this ecosystem. These essential ecosystem services can be facilitated through digital hubs.

Simultaneously, pioneering business concepts like the green economy, service economy, sharing economy, and industrial symbiosis are emerging in the market. These innovative notions form the foundation of both social and technological solutions for advancing a circular bioeconomy. The majority of transformative efforts in this realm center around the utilization of specific IT tools, including websites, applications, and consumer platforms.

In such a system, all stakeholders within the supply chain use certain IT tools that actively engage in overseeing processes along the complete value chain.

After considering the active incorporation of digital tools into economic processes and conducting a theoretical analysis of literature sources, we have identified specific domains where the integration of information technologies will generate added value within the bioeconomy. These domains include the inception of novel products, quality ecosystem services, the cultivation of untapped markets, the reduction of emissions and climate impact, and the promotion of judicious resource consumption and efficient utilization. In Figure 7, a conceptual representation elucidates the role of information technologies in nurturing the growth of bioinnovative ecosystems. Information technology solutions are categorized into four overarching groups, the implementation of which will play a pivotal role in facilitating the transition towards an innovative bioeconomy:

1. **Digital networks to connect supply chains between sectors, blockchain.**

The establishment of digital networks, often referred to as hubs, has opened up new avenues to make bioproducts accessible in emerging markets and industries. This is achieved through both vertical and horizontal integration facilitated by these digital networks. In the realm of consumer markets, the adoption of intelligent order fulfillment systems not only aligns with consumer needs but also expands product options and enables recommendations for sustainable consumption. Furthermore, digital networks enable the aggregation of products based on data-driven insights into the end-of-life cycle, thus promoting recycling and reusability of components. The utilization of Smart Design technology enhances this process. By incorporating digital tracking and process automation, resource utilization is optimized, leading to improved product composition assessment, enhanced product quality, and more effective waste sorting systems.

From a managerial and administrative perspective, digitalization offers real-time monitoring of transformation and development processes tailored to the specific requirements of target groups.

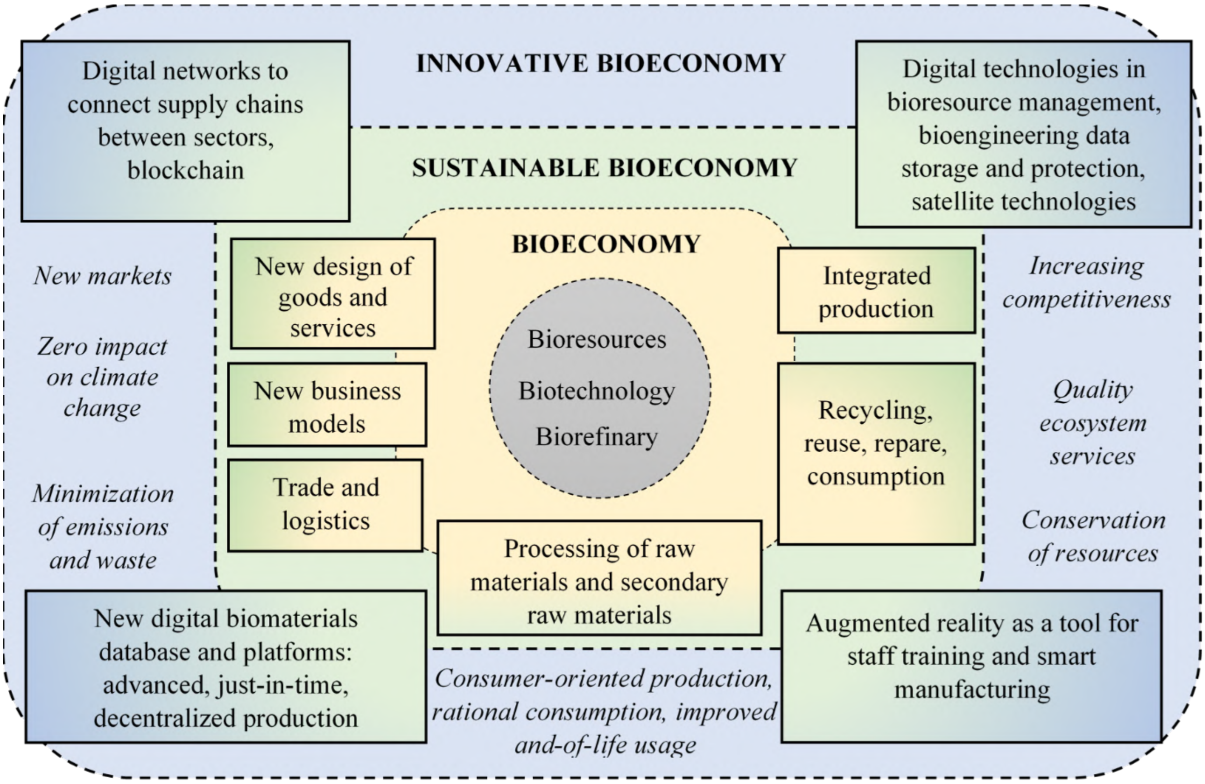

Figure 7: Conceptual model of the bioeconomic digital transformation based on sustainable development.

Information technologies enable operational control over processes such as lighting and water supply in greenhouses. They also facilitate the automatic procurement of raw materials and associated supplies, ensuring timely adjustments to production conditions. Smart Design technologies and digital tracking systems for product components extend product lifecycles and facilitate reprocessing, allowing them to serve as components in cascade production. Additionally, these technologies enhance the efficiency of biomaterial processing.

2. **Digital technologies in bioresource management, bioengineering data storage and protection, satellite technologies.**

Digital technologies in the management of bioresources make it possible to provide bioeconomy monitoring systems at the national, regional, and local levels by facilitating automated data flows. These flows help assess trends and the developmental potential of various innovative production processes. They can also be utilized to calculate reductions in CO_2 emissions. With the widespread adoption of information technologies, the creation of databases and rapid data processing and transfer become feasible, providing real-time information for effective management and production processes.

3. **New digital biomaterials database platforms: advanced, just-in-time, decentralized production.**

The integration of digital exchange activities and biomaterials platforms facilitates the enhanced accessibility of these resources for manufacturers, subsequently bolstering their utilization rates. The implementation of product component tracking systems grants stakeholders the ability to access intricate datasets (pertaining to aspects like purity and composition) concerning raw materials and other components, thereby facilitating more effective management of product quality. Conversely, the enhancement of production processes, brought about by the adoption of just-in-time supply systems utilizing IoT or machine-to-machine (M2M) communication tools, results in the streamlining of supply processes through navigation systems. Additionally, technologies like 3D printing are exerting a considerable influence on the advancement of decentralized manufacturing. For instance, the on-demand printing of wood-plastic composites exemplifies this trend, potentially paving the way for the establishment of compact, modular production facilities. These facilities could potentially employ small intelligent manufacturing systems (SIIMS) to further optimize their operations.

4. **Augmented reality as a tool for staff training and smart manufacturing.**

The use of augmented reality technologies makes it possible to develop and employ innovative methods in education [50], enabling virtual training for the operation of machinery and complex technological equipment within a simulated production environment. Concurrently, the implementation of smart manufacturing technologies facilitates the automated management of (bio)chemical and biotechnological processes. This, in turn, facilitates communication between production enterprises and the seamless transfer of data pertaining to the quality of final biomaterials throughout the value chain.

The combination of digital and biological transformation has the potential to significantly alter the design and management of production processes and their products. The 2018 Global Bioeconomy Summit workshop in Berlin was titled "The Great Convergence: Digitalization, Biologization, and the Future of Manufacturing". This workshop explored how "bio-intellectual value addition" could serve as a pivotal point or catalyst for bio-innovative shifts in the future of the bioeconomy. To foster an innovative bioeconomy, it is crucial to establish bio-innovative ecosystems grounded in knowledge and facilitate collaboration among diverse stakeholders. These ecosystems should serve as a starting point for developing an innovative bioeconomy. Creating a working group of various stakeholders, including academia, industry, and government, is essential in developing these bio-innovative ecosystems. By involving both public and private actors, this working group can collaboratively advance the ideas of an innovative bioeconomy, develop national action plans, and establish roadmaps for its progress

6. Conclusions

Over the last decade, Ukraine has experienced a decrease of over 4.6% in the share of industrial production in its GDP. These significant structural changes can be attributed to a combination of external and internal factors, including various economic and political processes. One crucial factor is Russia's annexation of industrial regions of Ukraine in 2014, which prompted the country to shift its economic focus towards stimulating the agricultural sector. This shift was accompanied by the creation of favorable conditions such as state subsidies and export promotion. However, the emphasis was not placed on the development of high- and medium-high-tech industrial production, resulting in increased foreign exchange earnings primarily through the export of raw materials rather than finished products.

During this period, Ukraine also enjoyed favorable conditions in foreign markets for exporting agricultural raw materials. However, the state's regulation of such exports in line with national economic interests was deemed ineffective.

With the recent full-scale invasion of Russia on Ukrainian territory, the situation is expected to deteriorate significantly for the Ukrainian economy. This invasion will likely lead to the deindustrialization of several industrial regions in Ukraine, which could have long-lasting effects spanning decades.

As a result, the level of technological and innovative products in the Ukrainian industry has significantly decreased. This situation, combined with social and political instability and the strengthening of globalization processes, poses potential risks to the country's economic security. The fact that most of the innovative products from domestic industrial production are not sold in the domestic market of Ukraine indicates the presence of systemic problems related to several macroeconomic factors (primarily the situation in specific markets) and a weak system of incentives and regulation for innovative activity, as well as the protection of national economic interests. Consequently, this leads to an imbalance in intersectoral relations within the economy.

The significant bioresource potential of Ukraine's economy, without the support of an innovative model of bioeconomic transformation, risks being reduced to a source of cheap raw materials without creating added value. Currently, the direction of green transformation is strategically important for Ukraine and holds high potential for developing and implementing innovations. However, this field's production, operational, and economic processes require reorganization and modernization using innovative approaches. The need for the development and implementation of innovations for bioeconomic transformation is thus very high. The resolution of this issue should be based on the development and implementation of scientifically grounded solutions, new biotechnologies, and innovations.

This process should not occur in isolation but involve all stakeholders. The creation of innovative bioeconomic ecosystems can serve as a platform for collaboration. National and international initiatives aimed at creating innovative bioeconomic ecosystems will provide opportunities for job creation, increased competitiveness of bioeconomic products, improved quality of ecosystem services, support for consumer-oriented production, and the reduction of resource loss and negative impacts on the climate.

In order to achieve the most effective results from the bioeconomic transformation of socio-economic systems, policymakers and managers should consider combining traditional approaches to innovation with experimental ones. This involves introducing and testing innovations in the real sector of the economy. The realization of this conceptual vision is made possible by the modern capabilities of information technologies. This article provides an overview of modern information technologies that can be implemented in the process of innovative bioeconomic transformation.

The rationalization of production processes through automation, robotics, and the use of artificial intelligence results in a significant decrease in employment in traditional industries. However, the bioeconomic transformation necessitates the development of new, highly specialized, and multi-disciplinary personnel to support the emergence of new sectors in the knowledge-based bioeconomy. These sectors involve utilizing new software in the digital economy, such as sharing economy platforms, blockchain, and satellite technologies for bioengineering and deep bioprocessing.

Managing complex adaptive systems, including the bioeconomy, is challenging. This is primarily because it requires coordination, extensive interaction within innovation networks, and constant adaptation to uncertain, nonlinear, and complex conditions. However, the processes occurring in such systems can lead to positive feedback effects, which form the basis for phase transitions and provide new positive attributes to socioeconomic systems. Consequently, creating innovative bioeconomic ecosystems aims to support the sustainable bioeconomic transformation of socio-economic systems. Therefore, an important area for future research is the development of information systems for managing the processes of bioeconomic transformation within innovative bioeconomic ecosystems.

References

[1] A. Pyka, Dedicated innovation systems to support the transformation towards sustainability: creating income opportunities and employment in the knowledge-based digital bioeconomy, Journal of Open Innovation: Technology, Market, and Complexity 3 (2017) 27. doi:10.1186/s40852-017-0079-7.

[2] J. Bell, L. Paula, T. Dodd, S. Németh, C. Nanou, V. Mega, P. Campos, EU ambition to build the world's leading bioeconomy—Uncertain times demand innovative and sustainable solutions, New Biotechnology 40 (2018) 25–30. doi:10.1016/j.nbt.2017.06.010, bioeconomy.

[3] M. S. Andersen, L. D. Christensen, J. Donner-Amnell, P. O. Eikeland, B. Hedeler, R. Hildingsson, B. Johansson, J. Khan, A. Kronsell, T. H. Inderberg, et al., To facilitate a fair bioeconomy transition, stronger regional-level linkages are needed, Biofuels, Bioproducts and Biorefining 16 (2022) 929–941. doi:10.1002/bbb.2363.

[4] I. Hryhoruk, V. Yakubiv, Y. Sydoryk, Y. Maksymiv, N. Popadynets, Modelling of prognosis for bioenergy production in Ukraine, International Journal of Energy Economics and Policy 11 (2021) 27–34. doi:10.32479/ijeep.11741.

[5] I. Virgin, M. Fielding, M. F. Sundell, Benefits and challenges of a new knowledge-based bioeconomy,

in: I. Virgin, E. J. Morris (Eds.), Creating Sustainable Bioeconomies: The bioscience revolution in Europe and Africa, Routledge, London, 2016, pp. 31–45. URL: https://tinyurl.com/3n42hm3f.

[6] Ministerium für Ernährung, ländlichen Raum und Verbraucherschutz, Ministerium für Umwelt, Klima, Energiewirtschaft, Landesstrategie Nachhaltige BioÖkonomie Baden-WÜrttemberg, 2019. URL: https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/6_Wirtschaft/Biooekonomie/Landesstrategie-Nachhaltige-Biooekonomie-barrierefrei.pdf.

[7] J. Dupont-Inglis, A. Borg, Destination bioeconomy – the path towards a smarter, more sustainable future, New Biotechnology 40 (2018) 140–143. doi:10.1016/j.nbt.2017.05.010, bioeconomy.

[8] C. Edquist, Systems of innovation perspectives and challenges, African Journal of Science, Technology, Innovation and Development 2 (2010) 14–45. URL: https://journals.co.za/doi/abs/10.10520/EJC10560.

[9] S. J. Herstad, T. Sandven, E. Solberg, Location, education and enterprise growth, Applied Economics Letters 20 (2013) 1019–1022. doi:10.1080/13504851.2013.772287.

[10] A. Klitkou, J. Bozell, C. Panoutsou, M. Kuhndt, J. Kuusisaari, J. P. Beckmann, Bioeconomy and digitalisation, Mistra Background paper, 2017. URL: https://nifu.brage.unit.no/nifu-xmlui/handle/11250/2612970.

[11] V. Vostriakova, M. L. Swarupa, O. Rubanenko, S. L. Gundebommu, Blockchain and Climate Smart Agriculture Technologies in Agri-Food Security System, in: A. Kumar, I. Fister Jr., P. K. Gupta, J. Debayle, Z. J. Zhang, M. Usman (Eds.), Artificial Intelligence and Data Science, Springer Nature Switzerland, Cham, 2022, pp. 490–504. doi:10.1007/978-3-031-21385-4_40.

[12] D. K. Karig, Cell-free synthetic biology for environmental sensing and remediation, Current Opinion in Biotechnology 45 (2017) 69–75. doi:10.1016/j.copbio.2017.01.010.

[13] Digitalization in life sciences: Integrating the patient pathway into the technology ecosystem, Technical Report 135128-G, KPMG International, 2018. URL: https://assets.kpmg.com/content/dam/kpmg/xx/pdf/2018/01/digitalization-in-life-sciences.pdf.

[14] A. Burgard, M. J. Burk, R. Osterhout, S. Van Dien, H. Yim, Development of a commercial scale process for production of 1,4-butanediol from sugar, Current Opinion in Biotechnology 42 (2016) 118–125. doi:10.1016/j.copbio.2016.04.016.

[15] M. Baker, 1,500 scientists lift the lid on reproducibility, Nature 533 (2016) 452–454. doi:10.1038/533452a.

[16] V. Gerbaud, M. Teles Dos Santos, N. Pandya, J. Aubry, Computer aided framework for designing bio-based commodity molecules with enhanced properties, Chemical Engineering Science 159 (2017) 177–193. doi:10.1016/j.ces.2016.04.044, iCAMD – Integrating Computer-Aided Molecular Design into Product and Process Design.

[17] D. Densmore, Bio-design automation: Nobody said it would be easy, 2012. doi:10.1021/sb300062c.

[18] Robotic labs for high-speed genetic research are on the rise: The design of synthetic lifeforms could become a new industry, 2018. URL: https://www.economist.com/science-and-technology/2018/03/01/robotic-labs-for-high-speed-genetic-research-are-on-the-rise.

[19] S. V. Murphy, A. Atala, 3d bioprinting of tissues and organs, Nature biotechnology 32 (2014) 773–785. doi:10.1038/nbt.2958.

[20] S. O. Ishchuk, L. Y. Sozanskyy, Comparative Statistical Assessment of Innovation Activity of the Industrial Sector of the Economy of Ukraine (Regional Context), Statistics of Ukraine 96 (2022) 74–58. doi:10.31767/su.1(96)2022.01.05.

[21] M. Kuznetsova (Ed.), Scientific and Innovation Activity in Ukraine. 2020, State Statistics Service of Ukraine, 2021. URL: https://ukrstat.gov.ua/druk/publicat/kat_u/2021/zb/10/zb_Nauka_2020.pdf.

[22] Yearbook of Industry 2020 – Poland, 2021, 2021. URL: https://stat.gov.pl/obszary-tematyczne/roczniki-statystyczne/roczniki-statystyczne/rocznik-statystyczny-przemyslu-2020,5,14.html.

[23] N. Burennikova, V. Kavetskiy, O. Lesko, R. Akselrod, O. Adler, M. Gregus, Modeling of the Investment Risks in Human Capital as the Factor of Enterprise Safety in the Context of the Stakeholder Theory, in: S. W. Pickl, V. Lytvynenko, M. Zharikova, V. Sherstjuk (Eds.), Proceedings of the 1st International Workshop on Computational & Information Technologies for Risk-Informed

Systems (CITRisk 2020) co-located with XX International scientific and technical conference on Information Technologies in Education and Management (ITEM 2020), Kherson, Ukraine, October 15-16, 2020, volume 2805 of *CEUR Workshop Proceedings*, CEUR-WS.org, 2020, pp. 213–221. URL: https://ceur-ws.org/Vol-2805/short16.pdf.

[24] I. Nikitina (Ed.), Table Input-Output of Ukraine at Basic Prices. 2019, State Statistics Service of Ukraine, 2019. URL: hhttp://www.ukrstat.gov.ua/druk/publicat/kat_u/2021/zb/05/zb_tvv_2019.pdf.

[25] Research and innovations, 2022, 2022. URL: https://ukrstat.gov.ua/operativ/menu/menu_u/ni.htm.

[26] K. Kokkonen, V. Ojanen, From opportunities to action - an integrated model of small actors' engagement in bioenergy business, Journal of Cleaner Production 182 (2018) 496–508. doi:10.1016/j.jclepro.2018.02.013.

[27] C. A. de Assis, R. Gonzalez, S. Kelley, H. Jameel, T. Bilek, J. Daystar, R. Handfield, J. Golden, J. Prestemon, D. Singh, Risk management consideration in the bioeconomy, Biofuels, Bioproducts and Biorefining 11 (2017) 549–566. doi:10.1002/bbb.1765.

[28] D. Lazarevic, P. Kautto, R. Antikainen, Finland's wood-frame multi-storey construction innovation system: Analysing motors of creative destruction, Forest Policy and Economics 110 (2020) 101861. doi:10.1016/j.forpol.2019.01.006, Forest-based circular bioeconomy: matching sustainability challenges and new business opportunities.

[29] L. Scordato, A. Klitkou, V. E. Tartiu, L. Coenen, Policy mixes for the sustainability transition of the pulp and paper industry in sweden, Journal of Cleaner Production 183 (2018) 1216–1227. doi:10.1016/j.jclepro.2018.02.212.

[30] D. Viaggi, Research and innovation in agriculture: beyond productivity?, Bio-based and Applied Economics 4 (2015) 279–300. doi:10.13128/BAE-17555.

[31] S. Elbe, C. Long, The political economy of molecules: vital epistemics, desiring machines and assemblage thinking, Review of International Political Economy 27 (2020) 125–145. doi:10.1080/09692290.2019.1625560.

[32] A.-A. E. Pigford, G. M. Hickey, L. Klerkx, Beyond agricultural innovation systems? Exploring an agricultural innovation ecosystems approach for niche design and development in sustainability transitions, Agricultural Systems 164 (2018) 116–121. doi:10.1016/j.agsy.2018.04.007.

[33] B. Salter, Y. Zhou, S. Datta, C. Salter, Bioinformatics and the Politics of Innovation in the Life Sciences: Science and the State in the United Kingdom, China, and India, Science, Technology, & Human Values 41 (2016) 793–826. doi:10.1177/0162243916631022.

[34] P. Huber, T. Hujala, M. Kurttila, B. Wolfslehner, H. Vacik, Application of multi criteria analysis methods for a participatory assessment of non-wood forest products in two European case studies, Forest Policy and Economics 103 (2019) 103–111. doi:10.1016/j.forpol.2017.07.003.

[35] P. T. Roundy, M. Bradshaw, B. K. Brockman, The emergence of entrepreneurial ecosystems: A complex adaptive systems approach, Journal of Business Research 86 (2018) 1–10. doi:10.1016/j.jbusres.2018.01.032.

[36] A. Ylimartimo, Case study on bioeconomy campus, central Finland, Biofuels, Bioproducts and Biorefining 12 (2018) 177–186. doi:10.1002/bbb.1739.

[37] M. Kircher, R. Breves, A. Taden, D. Herzberg, How to capture the bioeconomy's industrial and regional potential through professional cluster management, New Biotechnology 40 (2018) 119–128. doi:10.1016/j.nbt.2017.05.007, bioeconomy.

[38] M. Pagliaro, Preparing for the future: Solar energy and bioeconomy in the United Arab Emirates, Energy Science & Engineering 7 (2019) 1451–1457. doi:10.1002/ese3.440.

[39] S. S. Fong, Computational approaches to metabolic engineering utilizing systems biology and synthetic biology, Computational and Structural Biotechnology Journal 11 (2014) 28–34. doi:10.1016/j.csbj.2014.08.005.

[40] B. L. Wang, A. Ghaderi, H. Zhou, J. Agresti, D. A. Weitz, G. R. Fink, G. Stephanopoulos, Microfluidic high-throughput culturing of single cells for selection based on extracellular metabolite production or consumption, Nature biotechnology 32 (2014) 473–478. doi:10.1038/nbt.2857.

[41] M. I. Sadowski, C. Grant, T. S. Fell, Harnessing QbD, programming languages, and automation for reproducible biology, Trends in biotechnology 34 (2016) 214–227. doi:10.1016/j.tibtech.

2015.11.006.

[42] B.-J. Harder, K. Bettenbrock, S. Klamt, Model-based metabolic engineering enables high yield itaconic acid production by Escherichia coli, Metabolic Engineering 38 (2016) 29–37. doi:10.1016/j.ymben.2016.05.008.

[43] T. Ogunnaike, Can DNA hard drives solve our looming data storage crisis, 2016. URL: https://singularityhub.com/2016/10/21/can-dna-hard-drives-solve-our-looming-data-storage-crisis.

[44] J. Contreras, A. Rai, A. Torrance, Intellectual property issues and synthetic biology standards, Nat Biotechnol 33 (2015) 24–25. doi:10.1038/nbt.3107.

[45] C. J. Delebecque, J. Philp, Education and training for industrial biotechnology and engineering biology, Engineering Biology 3 (2018) 6–11. doi:10.1049/enb.2018.0001.

[46] I. V. Kholoshyn, O. V. Bondarenko, O. V. Hanchuk, I. M. Varfolomyeyeva, Cloud technologies as a tool of creating Earth Remote Sensing educational resources, CTE Workshop Proceedings 7 (2020) 474–486. doi:10.55056/cte.388.

[47] N. M. Lobanchykova, I. A. Pilkevych, O. Korchenko, Analysis and protection of IoT systems: Edge computing and decentralized decision-making, Journal of Edge Computing 1 (2022) 55–67. doi:10.55056/jec.573.

[48] Y. B. Shapovalov, Z. I. Bilyk, S. A. Usenko, V. B. Shapovalov, K. H. Postova, S. O. Zhadan, P. D. Antonenko, Harnessing personal smart tools for enhanced STEM education: exploring IoT integration, Educational Technology Quarterly 2023 (2023) 210–232. doi:10.55056/etq.604.

[49] O. V. Klochko, V. M. Fedorets, M. V. Mazur, Y. P. Liulko, An IoT system based on open APIs and geolocation for human health data analysis, CTE Workshop Proceedings 10 (2023) 399–413. doi:10.55056/cte.567.

[50] P. P. Nechypurenko, S. O. Semerikov, O. Y. Pokhliestova, An augmented reality-based virtual chemistry laboratory to support educational and research activities of 11th grade students, Educational Dimension 8 (2023) 240–264. doi:10.31812/educdim.4446.