Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Sustainable Rural Development in the Context of the Implementation of Digital Technologies and Nanotechnology in Education and Business

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The issue of ensuring sustainable rural development is increasingly critical for many countries, and it is especially urgent for Ukraine in light of the need to overcome the devastating consequences of full-scale aggression and revitalize rural areas. This study investigates the conceptual foundations of sustainable rural development and the challenges associated with their implementation, particularly through the integration of modern digital technologies and nanotechnology in education and business. The research supports the application of a quadruple helix model, where the collaboration between business, government, education, and the residents of the territorial community is feasible through the development of a robust civil society and the willingness of members to participate in social innovation. Nanotechnology is a transformative element in fostering sustainable rural development. By leveraging advancements in nanotechnology, such as precision agriculture, water purification, and the development of eco-friendly materials, rural communities can enhance productivity, sustainability, and overall quality of life. In this context, the functional role of education extends beyond traditional knowledge acquisition; it aims to cultivate individuals who understand the significance of social innovations, recognize their responsibility for societal transformation, and possess a sufficient level of digital competencies alongside a motivation for lifelong learning. Nanotechnology helps address some of the current challenges of rural development while positioning communities for a more sustainable and resilient future.

Keywords: digital competences, nanotechnology, model of rural sustainable development, local communities, social transformations, territorial communities, development strategies.

1. Introduction

The world is currently undergoing transformational processes that are unprecedented in scale, scope, and complexity compared to any previous human experience. These changes affect not only technology but also the fundamental philosophy of human existence. As a result, society increasingly recognizes the need to ensure a viable future for subsequent generations, which aligns with the concept of sustainable development and outlines its essential goals.

Within this context, the agricultural sector—and by extension, rural areas—plays a crucial role in implementing the Sustainable Development Goals (SDGs). However, there are significant challenges to achieving sustainable rural development, primarily stemming from the low level of innovation potential, which is exacerbated by insufficient targeted education and inadequate educational standards.

Presently, discussions surrounding the formation of "Industry 5.0," "Agriculture 5.0," and consequently "Education 5.0" are gaining traction in both academic and societal circles. The earlier concepts, Industry 4.0 and Agriculture 4.0, primarily focused on the creation of a digital economy and innovative technological advancements. However, they largely overlooked the necessity of addressing negative trends that could hinder the realization of the Sustainable Development Goals, particularly concerning environmental and social issues. The transition from Industry 4.0 and Agriculture 4.0 to Industry 5.0 and Agriculture 5.0 is both justified and necessary, as the previous paradigms proved to be predominantly technological frameworks that do not fully address the imperative needs outlined by the SDGs (Sobolevska, 2023). The establishment and implementation of Education 5.0 present opportunities for qualitative changes in labor potential, laying the groundwork for positive trends in rural development. However, the development of rural labor potential is currently complicated by the adverse demographic situation in rural areas (State Statistics Service of Ukraine, 2023).

Education 5.0 aims to facilitate better and more equitable access to relevant competencies for all members of society (aligned with the fourth Sustainable Development Goal), thereby creating conditions that support the achievement of other Sustainable Development Goals. Given this context, it becomes essential to investigate the factors influencing sustainable rural development in the digitalization era and to substantiate organizational and methodological approaches to facilitate it.

Based on the above considerations, the following problems can be formulated:

a. Is the state of sustainable rural development worse than that of urban areas?

b. Is there equal access to education in rural and urban locations?

c. Are there factors that cause resistance to the implementation of digital technologies in rural areas?

d. Which model of rural development best ensures the successful achievement of the Sustainable Development Goals?

One of the distinctive contributions of digital technology and nanotechnology to rural development and sustainability is how to integrate them into educational and business practices. Digital technology has changed the education and business world, from how people communicate and manage resources to data analysis. In a rural education context, integrating digital tools into the realm increases educational possibilities and prepares young people to engage in contemporary issues meaningfully. Additionally, nanotechnology has unprecedented opportunities for development in rural areas. As precision farming improves agricultural practices, water purification, and sustainable materials made from nanomaterial, nanotechnology can raise self-sustainability, reduce food loss, improve clean water, and so on. Mixed research of these two futuristic technologies can potentially change how people carry rural development and sustainability journeys.

This study assesses the theoretical basis of sustainable rural development from the perspective of incorporating digital technologies and nanotechnology into education and businesses through quadruple helix—the kind of cooperation between government, business, education sectors, and community residents, and how such a partnership can bring about social innovation and effects for the sake of sustainable change.

The role of educational systems in preparing individuals for the use of modern technologies, developing a higher level of digital competency, and fostering social responsibility is a key focus of this study. The integration of these measures is not just about technology use, but about empowering communities to bring about positive changes and ensure long-term sustainability and resilience. Therefore, the main aim of the study is to identify a successful model of sustainable rural development that leverages digital, nanotechnology, and social innovations, empowering individuals and communities to take responsibility for their future.

2. Theoretical Framework

Sustainable Rural Development

Sustainable rural development refers to the balanced pursuit of economic development, social equity, and environmental stewardship in rural areas. It embodies 'the ability to use renewable natural resources to meet the needs of the present without compromising the ability of future generations to meet their own needs' as emphasized by the Food and Agriculture Organization (FAO) of the United Nations in 2019. Core elements include food security, natural resource conservation, economic development, and social equity (FAO, 2019).

Both the terms 'rural development' and 'development of rural territories' are defined in the Concept of the Development of Rural Territories, marking the beginning of the strategic shift from state support for the agrarian sector of the economy to comprehensive rural development, 'leading to an increase in the quality of life and economic wellbeing of the rural population' (Verkhovna Rada of Ukraine, 2015). Sustainable rural development is traditionally seen as a process of extended production of rural space, which requires a balance between social, economic, and ecological components. Today, it is no longer possible to speak of the idea of sustainable rural development without referring to digitalization. And because of this, together with digital-for-development, the motto ICT4D, which means 'Information and Communication Technologies for Development,' has also become one of the most important concepts.

Despite a lack of consensus among researchers regarding the definition of 'rural development', all sources include the improvement of the living standards of the rural population as its core feature (Korinets, 2023). Nevertheless, this category is rather elusive because the interpretation and measurement of living standards rely on both objective and subjective criteria (Prati, 2023). Overall, experts tend to treat rural development as a trajectory of socio-economic change that is constant but does not have a uniform definition. Instead, the meaning and indicators of rural development are construed within a specific social and economic context.

The issue of sustainable rural development has become a significant area of scientific inquiry within the context of contemporary society. A notable example is the editorial by Castro-Arce & Vanclay (2020), who, after many years working on characterizing and contributing to the discussion on social innovations, now collect and disseminate evidence on the nature and role of social innovations for sustainable rural development. It is crucial to understand that interventions in sustainable rural development need to be flexible, adaptive, and work towards creating an inclusive and progressive space. They define adaptation as ‘the ability of a region to operate as a socio-economic system resilient enough to learn from experience and knowledge (exo-endogenous) and to be self-adjusting to changing or sudden pressures and processes of external and internal dynamics that enable its resilience for sustainable rural development’. In their scheme, they also highlight the significant role of social initiatives in promoting sustainable rural development (Castro-Arce & Vanclay, 2020). They provide an illustrative example of ADEZN, a nonprofit organization initiated by a university that supports diverse projects aimed at promoting sustainable practices across various fields, including:

- Regional development curricula and algorithms for training community members within educational institutions
- Public-private partnerships
- Supply chain systems for agricultural by-products, aligning with the principles of the circular economy
- Improvements in management and decision-making processes
- Land use planning
- Infrastructure development
- Management of natural resources

ADEZN has effectively coordinated local community activities and facilitated information exchange through discussion platforms. In the current context, leveraging such experiences through information and communication technologies (ICTs) is highly relevant and underscores the necessity of developing digital competencies among rural residents.

In parallel, the authors and social scientists Jeannerat & Crevoisier (2022) described the theoretical and methodological basis of the modern form of development policy, which they call 'creative' territorial development. This is based on combining the top-down and bottom-up policy adventurism that 'creates the conditions for co-innovation, entrepreneurship, reflection and institutionalization' in space and time. The scholars prescribe the promotion of tools of regional entrepreneurship, mutual learning, transfers of knowledge, creativity, and community-building through acts of business networking (Jeannerat & Crevoisier, 2022).

Related academic publications highlight how many researchers have staked out differing positions about how and why technologies contribute to the Sustainable Development Goals (e.g., Andersson & Hatakka, 2023; Prieto-Egido et al., 2023). In the work of Heeks (2020), digitalization is shown as a process of change and disruption affecting many aspects of modern life, particularly the role of digital technologies and ICTs in international development. Heeks (2020) views the changes brought by digitalization as so deep and novel that they amount to a paradigm shift in economic and political structures. The paradigm of 'digital technologies for development' captures this trend.

Thinking about ICTs as a vehicle to improve access, Me et al. (2023) find that the use of ICTs increases access to credit by 12.8% in rural areas and that rural households' income has grown due to the use of ICTs in China. They also show that the level of ICT perception and utilisation is significantly correlated with the levels of educational attainment. More specifically, the ICT use level by people with primary, secondary, and higher education is about 4%, 12.3%, and 18.6% higher, respectively. We already know that educational initiatives for rural development have played essential roles. The next step would be to study why ICTs' perception and use are associated with the level of education, which in turn can generate more activities for rural development.

In his contribution, Gorzelak (2021) examined the territorial dimension of social justice, observing that the most obvious problems with delivering social justice mandates are territorial systems that are facing real difficulties in Poland, for instance, as a result of depopulation. Domański's contribution (2021) used the knowledge on defining social justice and the variation in living standards between Poland's main regions as a reason to conclude that public policy should focus on equal citizen subjective opportunities for the foreseeable future.

Precision Agriculture and the Role of Nanotechnology

Modern technology offers access to a farm management concept termed precision agriculture, a farming approach known for its capability to monitor and manage intra- or inter-field variability of crops (Toriyama, 2020). Precision agriculture facilitates superior field-level management specifically for cultivation of crops and comprises multiple technologies from Geographic Information Systems (GIS) and Global Positioning Systems (GPS) to in-field sensors utilising remote sensing. This approach is crucial in addressing rapid and sustainable agricultural development to meet several challenges faced by humanity such as climate change, population growth and food security concerns. The integration of agriculture with nanotechnology through the advent of precision agriculture is a promising solution to these pressing issues.

Precision agriculture entails a detailed collection and analysis of data to guide crop production, guiding the decisions of farmers about such things as planting, fertilization, irrigation, and pest mitigation (Karunathilake et al., 2023). This dangerous supposition is based on the erroneous hypothesis that farmers, whether organic or conventional, are competing for the same land. The goal is to capture variability in the field so that inputs are used efficiently, and waste is minimized. At a more granular level, advances in precision technologies should potentially help farmers make decisions that are more conducive to mitigating the impacts of climate change by intervening in specific parts of a crop with specific needs so that action is only taken when necessary to reach a certain environmental, economic or social goal.

Nanotechnology is manipulating matter on an atomic and molecular scale, with instrumentation best measured in nanometres, typically in a range of 1-100 nanometres (Patel et al., 2021). So, we are talking about precision farming here. Specifically, nanotechnology enables several novel applications in agricultural practices with the development of nanomaterials and nanodevices that can help improve crop cultivation in the following ways:

i) Nano-fertilizers (nano-nutrients) and Nano-pesticides: Researchers have made several advances in the development of nano-fertilizers to improve the fertilizers' efficiency in nutrient delivery to crops and thus reducing the amount of fertilizer required and minimizing the run-off into the waterways. For instance, Al-Juthery et al. (2021) reported that applying controlled-release nano-fertilizer could improve the productivity of crops like tomato, wheat, and maize with reduced environmental footprints. Similarly, controlled-release nano-fertilizers are useful in soil management for the efficient production of crops with the reduced use of fertilizers, thus minimizing environmental issues.

ii) Soil and Water Management: Nanotechnology contributes to improving soil health and effectively using water. Nanosensors with real-time capabilities can monitor soil conditions like soil moisture content, nutrient composition, various pollutants, and other parameters, thus helping farmers make judicious decisions about achieving the optimal use of water and nutrients (Rakhimol et al., 2021).

iii) Plant Health Monitoring and Disease Management: Nanoparticle-based biosensors can detect plant diseases early and thus improve disease management, thereby enhancing plant health (Zain et al., 2023).

The application of nanotechnology principles and processes to precision agriculture is expected to yield significant environmental and economic benefits. As the efficiency of resource utilization (e.g., water, fertilizers, pesticides) increases, the environmental footprint of farming is expected to decrease, assuming that farmers can maintain the same levels of productivity. Acharya Pal (2020) reported that by reducing the input requirements in farming, operational costs decreased. With reduced overheads, the profit margin went up. Most importantly, precision agriculture equipped with nanotechnology can contribute to more sustainable practices and make the global effort to achieve food security more sustainable. As a key global society indicator of progress, the world faces the necessary and urgent pressure to produce more food, using fewer resources in the future, and we believe such a technology is an enabler.

Nanotechnology in Water Purification

Water shortage and clean water accessibility are some of the leading problems that humanity currently faces. Every year, pollution levels increase, and our water piping infrastructures age, with little addition to combat climate change. Traditional water treatment, while effective, is costly, produces copious amounts of waste, and has finite endurance before reaching the limits of its capabilities. In recent years, remarkable advancements in nanotechnology have emerged that can revolutionize how we treat water, leading to critical improvements in efficiency, affordability, and sustainability. Environmental contaminants such as heavy metals, pathogens, organic compounds, and microplastics threaten public health and the environment. As drinking water enters the water cycle, contaminants that were previously removed on their way to the surface can return, thereby jeopardizing the safety of a water source. According to estimates from the World Health Organization (WHO), more than 2 billion people worldwide cannot access safely managed drinking water services (WHO, 2023). The limited drinking water capacity that already exists is often lacking in purification measures and directly threatens public safety. A crucial aspect of improving water availability is the development of advanced water purification techniques that can remove contaminants at a lower cost and with less environmental impact than traditional techniques. Within the context of water purification, nanotechnology refers to some applications that enhance the capabilities of filtration or treatment processes:

a. Nanomaterials for Filtration: Carbon nanotubes, graphene oxide, and metal-organic frameworks are nanomaterials that have a large internal surface area and porosity, making them useful for filtration that can adsorb a wide range of bio-organic pollutants, including heavy metal and organic-compound contaminants, beyond what normal filtration technology can achieve (Mohan et al., 2021).

b. Nanoparticles for Remediation of Pollutants Different nanoparticles have been reported for antimicrobial activity and pollutant degradation. Examples include silver, zinc oxide, titanium dioxide, etc. These nanoparticles can be used in advanced oxidation processes (AOPs) to reduce the harmful toxicity presented by many organic pollutants and generate high-quality water (Cardoso et al., 2021). For example, great interest has been given to the investigation of titanium dioxide nanoparticles due to their photocatalytic activity, which can help achieve the oxidation of organic pollutants under UV light.

Some of the novel nanotechnology-based systems have high selectivity towards the removal of even minute contaminants such as viruses and bacteria; they also increase the rate of water throughput and reduce the overall energy utilization for the treatment processes. Nanoscale membranes enabled with nanomaterials have been applied in reverse osmosis and ultrafiltration systems, with higher efficiencies and lower energy requirements compared with conventional membranes. (Chadha et al., 2022). Nanotechnology integrated with existing methods such as biological filtration and chemical disinfection could create hybrid systems, having the benefits of other technologies (rather than one standalone treatment technology). The combination of nano-based technologies with classical methods will improve the efficiency of water purification systems while reducing chemical usage and the generation of wastewater (Khan et al., 2021).

As stated above, one of the first advantages of nanotechnology for water purification is the motivation it provides for sustainability. Nanotechnology opens the doors to more efficient water purification methods, making them more scalable and less water-consuming. Furthermore, using nanomaterials in water treatment would result in less aggressive chemicals and, consequently, a decreased environmental footprint. Environment-related questions remain open on the issue of nanoparticles leaching into the treated water and on the long-term ecological effects such a release of nanoparticles inside the environment might have. Regulatory frameworks and safety assessments will need to be developed to ensure nanotechnology-driven water purification systems without jeopardizing human health or environmental integrity.

Nanotechnology in Eco-Friendly Materials

The search for sustainable solutions to environmental crises has opened vast avenues for the development of green materials — primarily through the use of nanotechnology. As the need for practical yet environmentally friendly materials in the world market keeps increasing day by day, researchers strive to manufacture super materials that have higher efficiency yet fewer carbon footprints through the utilization of nanomaterials in making sustainable materials for the construction industry, packaging, cotton-based textile, medical devices, cosmetics, electronic gadgets, durables, and consumer goods. Eco-friendly materials are broadly defined as substances that are produced, exploited, used, and disposed of in a way that does minor environmental damage (Gayathri et al., 2022). Depending on how they are prepared, these materials are generally biodegradable, recyclable, or made from renewable resources. They are easily degraded without leaving any toxic residues and help save on natural resources by using reusable, recycled materials instead of new ones. Of great importance is the need for net zero industries, which prompts the need for industry to study the interactions of the production process with other natural resources, investigate the environmental mechanisms and methods of mitigation of adverse environmental impacts of their industrial processes like greenhouse effects, climate change, limitation of land as well as non-renewable energy use and duration of goods.

Nanotechnology, as the manipulation of materials at the molecular or atomic scale, holds the prospect of creating materials with better properties than can be obtained from conventional larger-scale manufacturing. Nanotechnology can be focussed on the development of eco-friendly materials and includes:

a. Biodegradable Nanocomposites: The synthesis of biodegradable nanocomposites that comprise natural polymers (such as starch or polylactic acid) reinforced with nanofillers (like nano clays or cellulose nanofibres). They are promising biomaterials with enhanced mechanical strength and thermal stability while being green to replace conventional polymers as more sustainable candidate materials for packaging and consumer products (Jagadeesh et al., 2021).

b. Nanotechnology in Coatings: Green coatings developed using nanotechnology impart protective properties while the ecological footprint of chemical coatings can be avoided. Nanomaterials can be made as water-based, solvent-free, and hazard-free coatings for significant improvement of physical properties, including reduction of carbon footprint when used as paints. Such nano structurally coated microspheres are hydrophobic and hence are effective against dirt and pollutants adhesion. The process enhances performance while necessitating less maintenance and non-cleaning operations, thereby further reducing their ecological footprint (Aithal et al., 2022). The application of nanotechnology in developing eco-friendly materials can include:

c. Energy-Efficient Materials: Research in nanostructured material can increase the energy efficiency of a wide-ranging technology we use every day. For instance, nanomaterials used in photovoltaic cells improve solar energy conversion efficiency. For example, using nanotechnology has resulted in significant advancements in solar power technology as a realistic and environmentally friendly solution to the renewable energy enigma (Khan et al., 2023).

Eco-friendly nanomaterials can be applied to numerous industries, and from textiles to building and packaging materials, they can take advantage of their unique properties. Nanotechnology is being applied in producing green textile solutions by creating water-repellent, stain-resistant, and antimicrobial materials without hazardous chemical treatments. Eco-friendly fabrics manufactured using recyclable or bio-based materials can offer improved duties and functions while retaining their biodegradability. Nanotechnology is opening opportunities to innovate solutions for sustainable building materials that can improve the energy efficiency of buildings while reducing waste. By protecting the concrete against corrosion, nanomaterials improve the durability of the material; consequently, fewer repairs or replacements are needed over time (Saleem et al., 2021). Modern farming technologies integrate nanotechnology to develop more resilient structures for farming processes. Nano-enhanced materials can be used in the construction of barns, silos, and storage facilities to increase insulation, strengthen the structure and create longer-lasting materials against the weather elements. Reducing energy loss and leakages is crucial for farmhouses. The application of nanotechnology can improve these facilities' overall energy efficiency, subsequently reducing maintenance expenses in the future. Eco-friendly packaging solutions incorporating nanotechnology can lower the environmental impact of disposable materials. Biodegradable packaging films can be nano-engineered to increase the strength of the materials and improve existing barrier properties in sustainable food packaging solutions.

Rural sustainable development requires innovation and cooperation, specifically with the digitalization of the rural economy and society and nanotechnological innovations. It needs to take advantage of the digital and nanotech advances that can be fostered precisely in the rural setting. This will enable the evolution of new solutions into the field and address several long-standing issues (such as the 'brain drain', the comparative disadvantage of rural economies and societies, and the isolation of rural communities).

We believe that many more studies on the impacts of Digital Technologies (DT) and Nanotechnology (NT) on sustainable rural development will come in the next few years. Research focus should be on evaluating the subsequent impacts of these technologies as RTD progresses. In our investigation of various partnerships between stakeholders (governments, academia, business, and residents), we realized that public policy should be prepared to establish more effective, inclusive co-ordinations.

3. Methodology

We present a research model as a structured methodology for investigating critical questions in the intersection of DT, NT, and sustainable rural development. It focuses on collaboration as a solution, gathering the synergies of different stakeholders to achieve sustainable development.

Objective of the Research: The primary objective of this research is to evaluate and substantiate the integration of digital technologies and nanotechnology into sustainable rural development, while utilizing the "quadruple helix" model to enhance collaboration among government, businesses, educational institutions, and community residents.

Theoretical Framework: The research is anchored in multifarious theoretical frameworks, including sustainable development principles, innovation diffusion theory, and the quadruple helix model, which emphasizes stakeholder collaboration in the advancement of rural development.

Research Design: Qualitative and Quantitative Approach: This study employed a mixed-methods design, combining qualitative and quantitative research methodologies to comprehensively analyze the current state of sustainable rural development initiatives and the role of technology.

Participant Selection:

1) Target Population: The study involved a diverse group of participants to capture a wide range of perspectives on sustainable rural development. The target population included: (a) Representatives from Local Government and Policy-Making Bodies: These individuals included local government officials and policy-makers who have direct influence over rural development initiatives and strategies. (b) Business Owners and Entrepreneurs: This group comprised individuals involved in agribusiness, local enterprises, and startups focused on sustainable practices, providing insights into the challenges and opportunities of implementing digital technologies and nanotechnology in rural settings. (c) Educators and Researchers: Participants included faculty members, researchers, and practitioners from higher education institutions who specialize in areas related to rural development, digital technologies, and environmental studies. (d) Community Members and Residents: This segment encompassed local residents engaged in community development initiatives, ensuring that the study reflects the needs and experiences of those directly affected by rural policies.

2) Sample Size: A total of 110 participant were selected to provide a broad representation of the different stakeholders involved in rural development. This sample size enhances the reliability and validity of the findings, allowing for a comprehensive understanding of the diverse opinions and experiences within the community.

3) Age Distribution:

- 18-24 years: 18 participants (16.4%)
- 25-34 years: 31 participants (28.2%)
- 35-44 years: 27 participants (24.5%)
- 45-54 years: 20 participants (18.2%)
- 55 years and older: 14 participants (12.7%)

5) Gender:

- Male: 46 participants (41.8%)
- Female: 54 participants (58.2%)

6) Occupational Positions: (a) Local Government Representatives: 20 participants who held positions as mayors, council members, or policy advisors. (b) Business Owners: 30 participants, including owners of agricultural businesses, eco-friendly startups, and local service providers. (c) Educators and Researchers: 35 participants, including professors,

lecturers, and researchers from universities and research institutions focused on rural studies and innovation in education. (d) Community Members: 25 participants from various backgrounds, including farmers, local activists, and volunteers involved in community improvement projects.

7) Recruitment and Selection Process: Participants were invited through a multi-faceted approach to ensure diversity and wide-reaching engagement. Invitations were disseminated via email newsletters, social media platforms, and notice boards at local government offices and educational institutions. Clear and engaging descriptions of the study's purpose and significance encouraged potential participants to consider involvement. Personal invitations were extended to known stakeholders within the community and sector through phone calls and face-to-face meetings to foster engagement and encourage participation. Informational sessions were held in local communities to discuss the importance of the study and invite residents to contribute. These sessions helped build trust and clarify the study's objectives.

8) Selection Criteria: Participants were selected based on their engagement in relevant sectors associated with rural development. Both willingness and availability to participate were taken into consideration, ensuring that those who truly had insights to share were included in the study. The selection process was designed to be inclusive, representing varied demographics and perspectives, which contributes to the robustness of the research findings.

Data Collection Methods:

- Surveys and Questionnaires: Data were collected through structured surveys that evaluated stakeholders' perceptions regarding digital technology usage, the effectiveness of current sustainable development practices, and the implementation of the quadruple helix model.
- Interviews: Semi-structured interviews were conducted with key stakeholders to gain deeper insights into the challenges and opportunities associated with integrating digital technologies and nanotechnology into rural development.
- Document Analysis: The research included an analysis of relevant regulatory acts, targeted programs, and existing literature on sustainable rural development and technological integration to contextualize the study.

Data Processing and Analysis:

- Statistical Analysis: Quantitative data from surveys were processed using statistical software to determine correlation and significance of findings related to the implementation of Sustainable Development Goals (SDGs).
- Thematic Analysis: Qualitative data from interviews were transcribed and analyzed thematically, identifying key patterns and insights relevant to the research focus.

Integration of Findings: Using the quadruple helix model as a theoretical description of the technological strategies considered, integrating both qualitative and quantitative findings allows us to maintain an overall balance in assessing which part of the helix supports which to sustain rural development in the long run.

Practical Implications: The conclusions of this research offer a structured plan of action for policymakers, schools and neighborhoods advancing the adoption of digital technologies and nanotechnology in a sustainable way.

Future Research Directions: Going forward, it would be beneficial to investigate the longer-term effects of integrating technology into rural development, consider the potential for scaling up successful approaches, and evaluate possible resistance to adopting these types of technologies on a larger scale. For example, further studies should identify potential causes and propose effective strategies to address the bottlenecks associated with implementing these technologies. Furthermore, more work should be done to understand how stakeholder participation can favorably impact the sustainability of these technological innovations.

4. Results and Discussion

The data collected through this study provideв valuable inputs to the evolving agenda for sustainable rural development, which employs digital technologies and nanotechnology in education and business. The 110 participants' survey findings indicated their experience and perceptions of the subject matter, as well as recommendations from the stakeholders.

Perspectives on Digital Technologies

Respondents were asked to gauge their perceptions regarding the advantages and obstacles accompanying digital technology integration in rural development. They indicated the following:

1) Benefits of Digital Technology:

- 82% reported enhanced access to information and resources through digital tools.
- 75% noted improved communication between stakeholders as a significant advantage.

2) Challenges Faced:

- 60% expressed concerns related to the digital divide, indicating that some rural residents lack access to the necessary technology.
- 55% identified insufficient training and digital literacy as barriers to effective implementation.

Use of Nanotechnology in Rural Development

The potential of nanotechnology to advance sustainable rural practices was assessed, with responses indicating varying levels of awareness and application:

1) Awareness of Nanotechnology:

- 73% of participants stated they were familiar with basic concepts of nanotechnology and its applications in agriculture and resource management.

2) Current Applications:

- Among those aware, 45% reported that nanotechnology is currently being utilized in local agricultural practices, such as in fertilizers or pest control.

Participant Insights on Collaboration

The collaborative nature of the quadruple helix model was explored through the participants' perspectives on partnerships among business, government, education, and community members.

1) Importance of Collaboration:

- 90% of participants emphasized the necessity of collaboration among the four sectors to achieve sustainable development objectives.

- 85% of respondents acknowledged that effective partnerships have led to successful initiatives in their communities.

Recommendations for Improvement

Participants provided insightful recommendations to enhance the integration of digital technologies and nanotechnology in rural development:

1) Training Programs:

- 92% of participants called for the establishment of training programs focused on improving digital literacy among rural residents.

- 89% suggested workshops that demonstrate the practical applications of nanotechnology in agriculture and business.

2) Policy Support:

- 87% recommended that local governments develop supportive policies and regulations to encourage technological adoption.

These data shed light on the participants' perceptions of and insight into the influence of digital technologies and nanotechnology on rural sustainable development projects, as well as the challenges involved in promoting the adoption of these digital technologies.

The participants' preferences show that the use of digital tools has the potential to improve information access and communication in rural areas and the real-time implementation of development projects. For instance, one of the participants acknowledged that these digital tools can enhance knowledge sharing among different groups, including farmers, schools, and the community, which in turn allows them to reduce tedious work and improve their productivity. Equally, 82% of the respondents were aware that access to digital resources, including computers, tablets, smartphones, and the internet, could enhance information and resources compared to traditional publications and journals. Meanwhile, 75% of the participants that answered positively highlighted that improved communications between development actors such as local government, business people, and residents due to the use of digital tools contributed to efficient and effective programming of rural development projects.

Regardless, the barriers identified by the participants suggest key areas that must be addressed to integrate technology successfully. The fact that 60% of respondents mentioned the digital gap as a concern point to a significant barrier to the equitable distribution of digital resources. Rural residents need access to technology, which they could have access to in urban areas, and they need internet access as a basic resource to access the rest of the digital resources. This represents an important risk of reducing inequalities within the rural area by amplifying them, putting more marginalized people on the sidelines of digital development.

Moreover, 55%of the respondents considered that there were no courses or insufficient training to facilitate digital literacy as barriers to implementing technology effectively. This draws attention to developing educational programs to improve digital literacy. It is clear that even if technology is available, without the training to use it properly, those technologies will not be implemented to the most excellent effectiveness, and those who use digital technologies must be taught to navigate them to maximize their usage successfully.

There was a significant variation in the levels of awareness and application among the participants. We asked about basic concepts of nanotechnology, and 73% reported that they were generally aware of them. This indicates an emerging interest and confidence in the applicability of nanotechnology and its benefits for agriculture and resource usage in rural areas. This is an essential part of readiness for the adoption of nanotechnology, which has been shown to be useful for increasing the efficiency and productivity of agricultural practices.

It was promising to find that 45% of them said that nanotechnology was introduced into local agricultural operations in order to accommodate sustainable production. The use of nanotechnology can enhance satisfactory production while minimising the use of chemicals as well as other kinds of farming interventions. It was a positive sign of the sustainable production agenda by the application of specific nano-fertilizers and nano-pesticides to enhance the farming outcomes and benefit the farmer's economy while at the same time maintaining the quality of the natural resources.

A component of the quadruple helix model is the idea of shared governance: reaching out, listening, and learning from others. When we asked how important principal stakeholders are in these collaborative initiatives, we found that they were indeed seen as essential. Overall, 90% of those answering our survey felt that collaboration between business, government, educational, and community stakeholders is necessary, supporting our recommendation that partnerships across multiple sectors will be critical to achieving sustainable development objectives. This level of consensus suggests a strong understanding among the participants of how to attain greater outcomes through collaboration between sectors. This same sense of consensus is also evident when encouraging stakeholder collaboration was included in Grand Valley's county strategic plan for the next 30 years: we asked how many effective partnerships for local projects have achieved tremendous success, and 85%t of respondents agreed that they had been able to achieve successful projects because of these partnerships. Engaging multiple stakeholders can result in the sharing of expertise, as well as financial and human resources, that may only be available in some sectors. This sharing enables innovative solutions to emerge that may be unavailable in an isolated sector.

Our participants introduced concrete ideas for strengthening the links between the integration of digital technologies and nanotechnology and rural development. So, 92% called for training programs on improving digital literacy among the rural population, which we have to be serious about; it is time educational efforts were invested in. Training programs, lecture series, and providing access to online tutorials and workshops can strengthen the digital divide and improve the capacity of the community members to use digital technologies well. Also, 89%

proposed workshops on nanotechnology applications in digital technology and agriculture/business. Such seminars can help 'de-mystify' nanotechnology, making it more palatable and less threatening, which would further strengthen its adoption process and make sure that the local stakeholders are informed about how those technologies can be applied. Finally, there was a call from 87% for local governments to come up with supportive policies and regulations regarding nanotechnologies and digital technologies. Policymakers need to be proactive about the future, and formulating the right policies to encourage innovation and support local efforts can enable the technologies to be integrated into the rural development schemes.

These outcomes demonstrate the importance of digital technologies and nanotechnology as crucial factors in increasing sustainable rural development. Even though their benefits in rural development have strong recognition, the main challenges of access and the lack of adequate training need to be addressed and improved before and during the implementation of these innovations. With a concerted effort of collaboration between different stakeholders (Hutsaliuk et al., 2020a,b) as well as the investment in education and policies, rural communities could attract widespread application of these innovations to contribute to a more sustainable and resilient future of rural communities, improving the wellbeing of the rural residents. The results of this project highlight that access to, and widespread application of technology is critical to increasing the resilience and sustainability of rural communities, ensuring overall and universal rural development.

Connection with the Human Development Index (HDI)

Based on three key dimensions of human development — health, education, and standard of living — the Human Development Index or HDI is a measurement used to assess or indicate the overall development of countries. It is the direct measure of individuals' well-being and quality of life in specific areas. As an essential metric of a country's sustainable rural development program, the HDI is a handy indicator of rural development that helps understand whether the usage of digital technologies and nanotechnology in a development model has increased human development outcomes. The United Nations also uses the same index annually to calculate the ranking of the states (Stavytskyi & Sachko, 2020).

In our view, it is advisable to incorporate the level of ICT usage into the aggregate indicator when evaluating the quality of life. This inclusion could provide a more nuanced understanding of the socio-economic dynamics in rural areas and further facilitate effective policymaking aimed at sustainable development. The average monthly wage by type of economic activity for the three quarters of 2023 in Ukraine is shown in Figure 1.

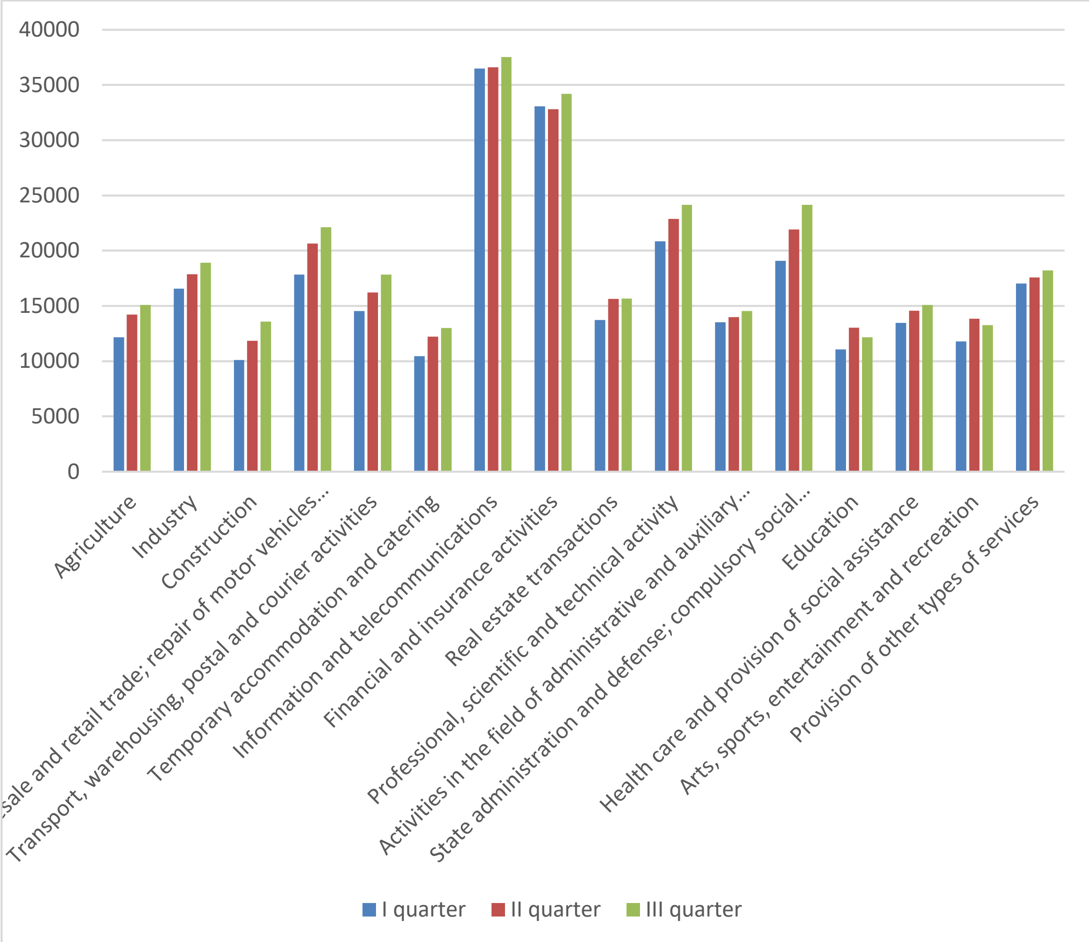

Figure 1. Average monthly wage by type of economic activity for three quarters of 2023, UAH

Source: Compiled by the authors based on data from the State Statistics Service of Ukraine (2023).

For illustration, the average monthly salary in agriculture in the first three quarters of 2023 was below the national average. Table 1 shows the distribution of Ukraine's population by type of area.

Table 1. Distribution of Ukraine's population by type of area, as of the beginning of the year (%)

Type of area	Years									
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Urban	68,9	69,0	69,1	69,2	69,2	69,3	69,4	69,5	69,6	69,7
Rural	31,1	31,0	30,9	30,8	30,8	30,7	30,6	30,5	30,4	30,3
Total	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0

Source: Compiled by the authors based on data from the State Statistics Service of Ukraine

(2023).

Accordingly, the proportion of the rural population of Ukraine over the past nine years has been characterized by a steady, albeit slight, decline (by 0.8% over nine years), which can be defined as a negative trend.

The mortality rate per 1000 persons of the current population of Ukraine (Figure 2), the mortality rate of children under the age of 5 per 1000 live births in rural areas is higher than in urban areas (Figure 3), and the number of maternal deaths per 100,000 live births in rural areas is also significantly higher (Figure 4).

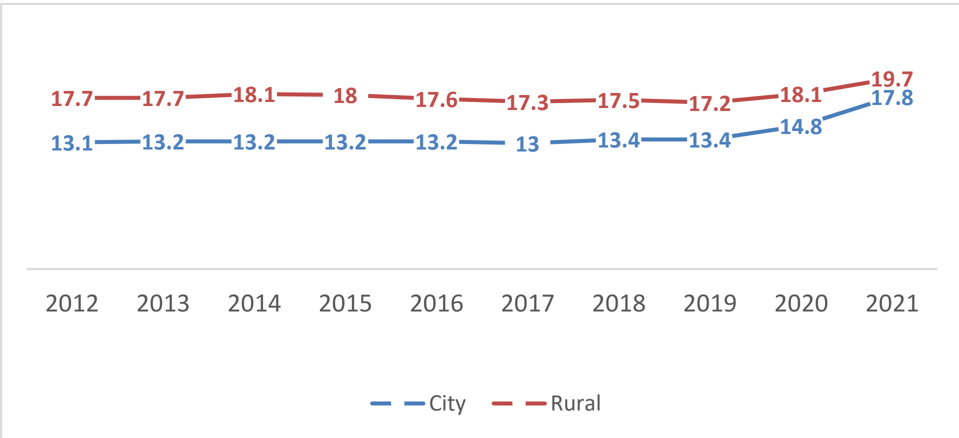

Figure 2. Mortality rates per year per 1000 persons of the current population of Ukraine by type of area

Source: compiled by the authors based on data from the State Statistics Service of Ukraine (2023).

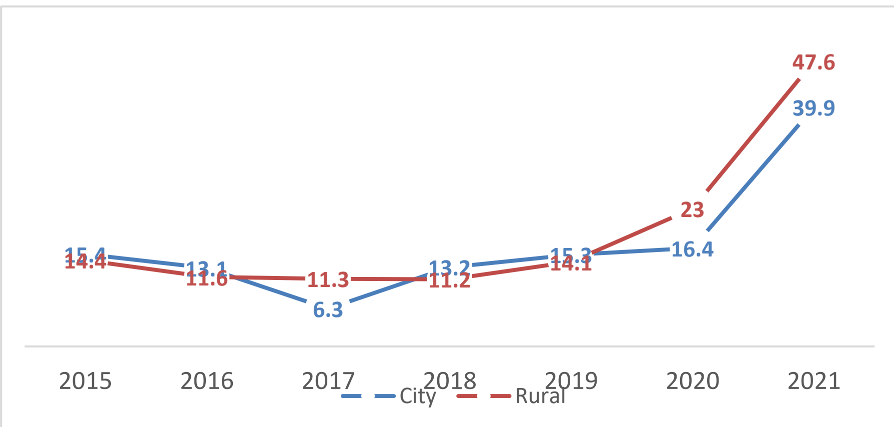

Figure 3. Number of maternal deaths per 100,000 live births by type of area

Source: compiled by the authors based on data from the State Statistics Service of Ukraine (2023).

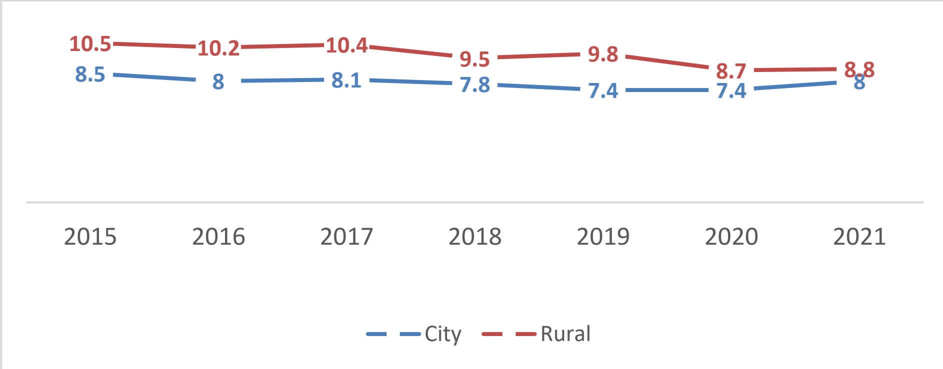

Figure 4. Mortality of children under 5 years of age, cases per 1000 live births by type of area

Source: compiled by the authors based on data from the State Statistics Service of Ukraine (2023).

Figures 2, 3, and 4 indirectly indicate that the quality of life in rural areas is lower than in urban areas, which necessitates the development and implementation of measures aimed at improving these indicators in the context of the Sustainable Development Goals.

In accordance with the Sustainable Development Goals, it is very important to ensure inclusive education for all who need it. On the negative side, there is a much smaller share of full-time general secondary education institutions with inclusive education in rural areas than in urban areas (Figure 5).

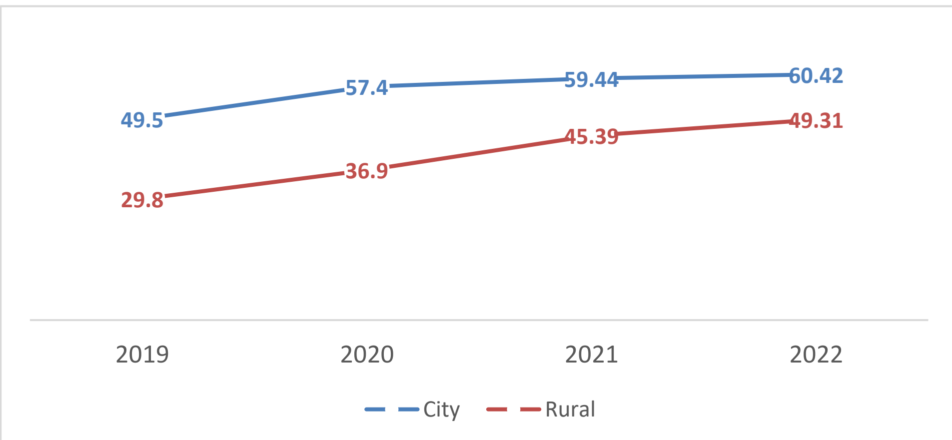

Figure 5. Share of full-time general secondary education institutions with inclusive education by type of area, %

Source: compiled by the authors based on data from the State Statistics Service of Ukraine (2023).

The current reduction of secondary education institutions in rural areas may lead to an increase in this gap. With regard to information and communication technologies, the share of general secondary education institutions in rural areas that have access to the Internet and use computers in the educational process is quite high, although characterized by negative dynamics (Figure 6).

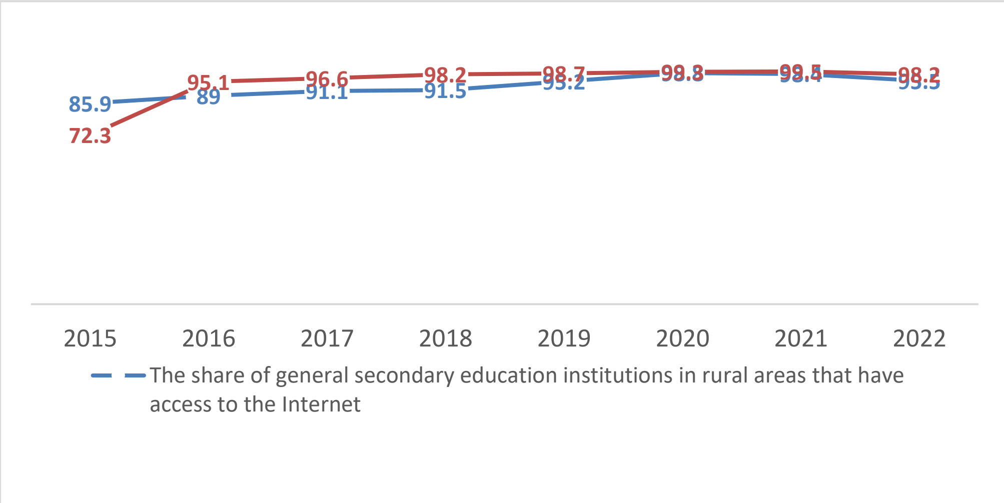

Figure 6. Introduction of ICTs in general secondary education institutions in rural areas, %

Source: compiled by the authors based on data from the State Statistics Service of Ukraine (2023).

Thus, it can be assumed that general secondary education institutions in rural areas in Ukraine are currently provided with sufficient ICT. However, the question remains as to the possibility of their optimal use.

When analyzing the differences between theories of development and social transformation, scholars emphasize that education only in the broad sense of non-formal learning and in interaction with knowledge is directly related to social change, because such education leads to a transformation of thinking (Robinson-Pant, 2023). Scholars studying the relationship between education and social development have an ambiguous view of what comes first – education or social change.

Hence, it is important to interpret education as a component of the realization of human rights in the context of its provision by a certain political program. In our opinion, the functional load of education, especially when taking into account the needs of rural development, is primarily to prepare a person who understands the importance of social innovations is aware of his or her own involvement in social transformations, has a sufficient level of digital competencies and motivation for lifelong learning. Modern innovative production, organizational, and financial technologies aimed at ensuring efficiency gains require a high level of digital competencies from production personnel, managers, and investors (Karnaushenko et al., 2023).

In rural areas, education has traditionally been associated exclusively with schooling, but in the context of the Sustainable Development Goals and the specifics of rural areas, it is necessary to consider education more broadly and in the context of social change, which does not diminish the need for a balanced approach to decisions regarding schooling.

The digital transformation of education is a process of technological and organizational change that is primarily associated with the development of digital technologies. Transformations of educational approaches are caused by their adaptation to the changing educational environment, which necessitates continuous training of employees and students. This implies access to technology and technological literacy for all members of society, which is a problem for Ukraine today. These problems are often referred to as the digital divide, which is calculated as the difference (ratio) between the ability of different people to access the Internet and digital technologies (Lythreatis et al., 2022; Mathrani et al., 2022).

The reasons for the digital divide are usually determined by technological and social factors and are mostly caused by insufficient access to ICT and a lack of digital skills, the development of which is one of the most important elements of students' future full and active participation in public life. According to the International Telecommunication Union’s “Facts and Figures 2023”, steady but uneven progress in global Internet connectivity highlights the existence of a digital divide (ITU, 2023).

Thus, in 2023, 81 percent of urban residents worldwide had access to the Internet, while in rural areas this figure was only 50 percent of the population. The urban-rural gap, measured as the ratio of these two percentages, has remained virtually unchanged in recent years: 1.7 in 2020 and 1.6 in 2023 (Measuring digital development: Facts and Figures, 2023). A problem for the agricultural sector is the low level of digital literacy of the working population. Thus, according to the results of a sample survey, 61% of the surveyed farm managers recognize the insufficient level of digital maturity of the farm and critically assess the level of digital competencies of both personal and employee employees.

Different sizes, organizational and legal forms, and models of management represent agricultural enterprises. Along with agro-holdings that have a complex territorial structure with subsidiaries geographically dispersed, there are small ones, mostly represented by farms and peasant farms, which have different levels of digital competence of their staff and access to digital technologies. We believe that when assessing the digital divide, it is advisable to take into account not only the technical capabilities of access to Internet resources but also the level of digital maturity of business entities and the digital competencies of rural residents.

The digital divide is observed not only between rural and urban residents but also between employees of agricultural holdings and other business entities. Unlike large agribusinesses, Ukrainian small agricultural producers are focused on the domestic market, which means that they currently ensure the country's food security and improve living standards in rural areas (Kononenko et al., 2022). Small agricultural enterprises are a rural saving model of doing business, and they ensure comprehensive sustainable development of rural areas and preservation of the rural settlement network (Sabii, 2021).

However, the very agricultural producers that correspond to this model face significant problems with material and technical, human resources, high production costs, lack of markets, etc. In today's business environment, overcoming these problems and ensuring competitiveness is directly related to the formation of digital competencies of members of rural households, owners, and employees of agribusinesses within the framework of the concept of a “learning region”.

Accordingly, we consider the formation of digital competencies as a prerequisite for the effective implementation of the concept of a learning region and a tool for the competitiveness of small agricultural businesses, which is especially relevant in the context of ensuring the revitalization of business and rural development in the post-war period in Ukraine. Therefore, it is necessary to substantiate organizational models for the development of the territorial community that is being trained. At the same time, the formation of digital competencies is a prerequisite for the effective implementation of the concept of lifelong learning and ensuring the preservation and development of small agricultural producers. We join the position of scientists regarding the priority of the development of individual, farm, family farms, and small and medium-sized agricultural enterprises as the basis for sustainable rural development and preservation of the settlement network.

In the context of European integration, the experience of European countries concerning social transformations in the countryside is interesting for Ukraine, in particular about the implementation of the LEADER Project (Nordberg et al., 2020). This Project aims to improve the well-being of the rural population through community-led local development (CLLD) based on the population's involvement and internal resources. Local initiative groups encourage local NGOs and businesses to test new ways to develop their territory and use regional assets. A thorough study of rural development and the formation of new social relations based on social innovations was conducted by Nordberg et al. (2020). These scholars consider the organizational mechanism for forming social relations to meet local needs and ensure rural development.

Similar circumstances cause the problems of rural development in European countries to those in Ukraine (migration, urbanization, etc.). In Ukraine, these problems are deeper and are exacerbated by full-scale military operations. These scholars see social innovations as the solution to these problems and the source of rural development. They consider different models of rural development such as exogenous, endogenous, and neo-endogenous (which is a synthesis of the first two) and emphasize that the latter meet the conditions for the formation of social innovations.

According to Ray (2006), the theory of neo-endogenous development is based on local resources and is characterized by dynamic interaction between local areas and the wider environment, promoting both internal local connections and connections with the external environment.

Researchers traditionally argue for the need to implement cooperation between business, science, and public administration (called the “triple helix”) as a model of innovative development (Figure 7).

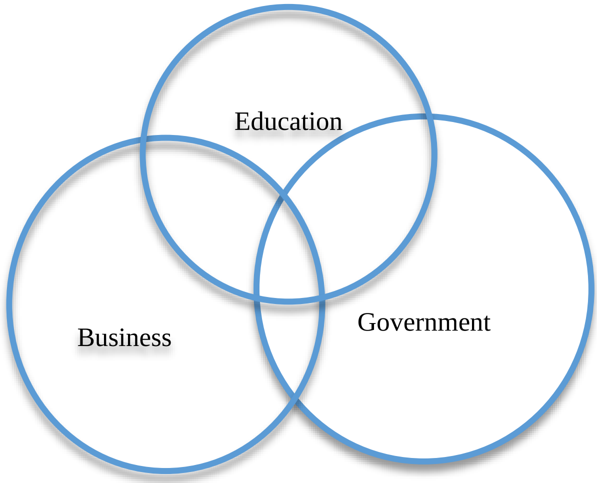

Figure 7. The triple helix model of rural development

Source: developed by the authors on the basis of research by Zhou & Etzkowitz(2021), Hernández-Trasobares & Murillo-Luna (2020), Li et al. (2020)

Today, when justifying the optimal model of rural development, scholars increasingly consider the "quadruple helix" (Irungu et al., 2023), which covers the interconnections and cooperation between such sectors as business, government, education, and the residents of the territorial community (Figure 8).

This model has proven successful in terms of the emergence and spread of social innovations aimed at rural development and is appropriate for Ukraine.

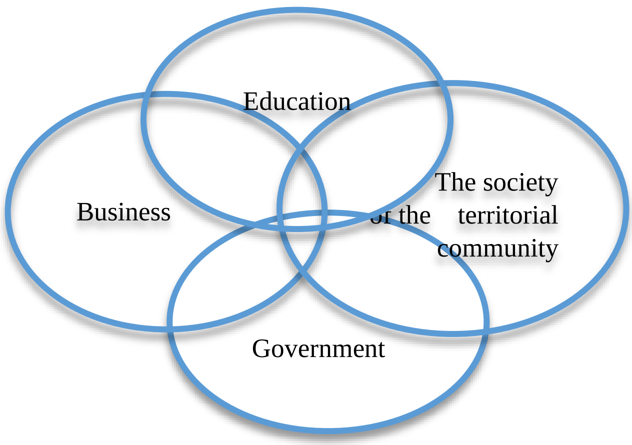

Figure 8. The quadruple helix model of sustainable rural development

Source: developed by the authors on the basis of research Irungu et al. (2023), Hasche et al. (2020), Malik et al. (2021)

Local communities that are directly connected to the others represent the fourth spiral in the quadruple helix: companies, the public sector, and educational institutions. People in civil society may belong to other spheres of their working lives (e.g., teachers, civil servants, businesspeople, or workers), but in civil society, they represent citizens and the fourth spiral. Individuals are crucial because they link the spirals and communities as intermediaries. The drivers of social innovation are diverse and can include firms, local governments, research and education institutions, and local NGOs, but more importantly, communities (civil society) play a role in social innovation. At the same time, participants play different roles as initiators, developers, or implementers of social innovations, which can be presented as certain projects. Suitner et al. (2024) consider social innovations in the context of resource conservation and energy transformation, which is directly in line with the Sustainable Development Goals.

According to scholars Irungu et al. (2023), with whom we agree, the quadruple helix is an extension of the triple helix model, which did not allow for the conceptualization of knowledge transfer interactions in rural areas, where the innovation system is increasingly open to different stakeholders. Achieving sustainable rural development is a complex task. Implementing a strategy for revitalizing rural regions based on the four-pronged model will help overcome the crisis and use institutional advantages to ensure the survival of small farms.

5. Conclusion

Based on the study, synthesis of scholarly works, analysis of statistical information, and the results of our research, it has been found that the current state of sustainable rural development in Ukraine is unsatisfactory, with its level notably lower than that of urban areas. According to the statistical data, while rural areas in Ukraine demonstrate a sufficient level of access to information and communication technologies (ICT) within general secondary education institutions, the effectiveness of their usage remains problematic. There exists a digital divide between rural and urban areas, a trend that is observed globally. This assessment of the digital divide is based on comparing access to the Internet and information technology. When accounting for the level of digital competencies, this gap in Ukraine is significantly wider, as confirmed by the results of our questionnaire surveys.

Agricultural enterprises in Ukraine represent a variety of sizes, organizational forms, and management models. These include large-scale agro-holdings with a complex territorial structure and territorial dispersal of units, as well as smaller farms and peasant households. Any kind of enterprise can be characterized by unequal distribution of staff digital competencies and opportunities to access different digital technologies. When composing indicators for measuring the digital divide, it is important to look not only at technical opportunities to access internet resources but also at the digital maturity of business entities and the digital competencies of rural residents. The digital divide contains technical and social components, and the socio-technical processes of transitioning through it are connected to more general social transformations and the development of innovative upstream projects. Without creating digital competencies in rural people and increasing digital accessibility, it will be impossible to reduce the access gap between rural and urban areas in the educational sector — and, more importantly, to implement the learning community concept and the lifelong learning approach. This social and academic approach is also essential for preserving traditional rural geographical patterns and supporting the competitiveness of small producers, especially in the post-war period when it was critical to recreate the small agricultural sector to advance the rural area. Among rural development models currently being used, neo-endogenous ones are the most effective when they focus on social innovation, explore local resources, and orient local subjects to interact with the external environment. Such subjects might be a single city or country, with a focus on stimulating their development. This approach creates conditions for defining common goals and joint actions for progress. A further step is to extend this model to the triple helix, where business, science, and public administration become the three processes leading to development, including the local community in certain areas, as a quadruple helix model. This is an important and conceptually interesting approach because of the critical role played by social innovation, which is made possible in such an approach because of the presence and intensity of the interaction between local areas and the environment. It works especially well when civil society has taken a step forward in forming itself and preparing its members for such social innovation.

Nowadays, digitalization is considered a primary driving force in supporting both rural development and sustainable development. Providing good conditions for digital competencies among rural residents and delivering high-quality teaching and learning environments will play a significant role in supporting rural growth. The essential functional job of the education sector is to cultivate in individuals the awareness of social innovation and their responsibilities for social transformation and to provide them with adequate digital competencies and motivation for lifelong learning. Another important avenue for both rural development and sustainable development is nanotechnology. Nanotechnology can be applied in agriculture to improve farming techniques. In the years to come, if applied astutely, nanotechnology can help rural areas solve water or community health problems (e.g., making faster virus preparation to treat fatal sicknesses in rural regions more rapidly).

Future research will be directed towards elaborating the mechanisms in the framework of the model of sustainable rural development in the context of digitization, stressing above all the cooperative and competitive cooperation of the rural development stakeholders. In this way, we hope to create a promising scenario for the sustainable future of the regions with rural areas in Ukraine.

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