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DEFINING FOCUS AREAS FOR EXPERT ASSESSMENTS ON THE IMPLEMENTATION OF DIGITAL TECHNOLOGIES IN THE AGRO-INDUSTRIAL SECTOR

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The article addresses the challenge of determining priorities for the implementation of digital technologies in agro-industrial enterprises, particularly in the crop production sector, under conditions of limited resources, finances, and personnel. Modern agricultural businesses face increasing pressure to enhance operational efficiency, making the adoption of digital solutions ever more relevant. However, in light of limited resources and a lack of experience with such technologies, selecting priority areas for their implementation is critical.

The authors propose using a fuzzy expert evaluation methodology based on linguistic variables. This approach enables the consideration of uncertainties and ambiguities that are characteristic of the early stages of digitalization in the agro-industrial complex. An expert group, comprising specialists in agriculture and digital technologies, was involved in assessing the most promising areas for implementing digital solutions. Through the use of fuzzy set theory, the expert evaluation results were processed, allowing for an objective determination of digitalization priorities.

The study found that, from the perspective of digital technology application goals, the highest-rated areas were crop monitoring and programming, informatization, and the creation of a digital agronomist model. The introduction of these technologies would significantly improve the management of production processes, increase yields, and ensure more rational use of resources, while minimizing losses.

Ultimately, the research outlines concrete priorities for the implementation of digital technologies in crop production, which promise to provide substantial benefits to the agro-industrial sector. The findings suggest that strategically targeted digital solutions can drive productivity improvements and ensure more sustainable practices, reinforcing the importance of adopting advanced technologies in modern agriculture. This study underscores the need for careful consideration of resource allocation and expert guidance to maximize the potential of digitalization in agricultural enterprises.

***Key words:** digital technologies, expert assessments, linguistic variables, management decisions, autonomous information management systems, enterprise programming.*

Лобода О. М. Визначення пріоритетних напрямів експертних оцінок для впровадження цифрових технологій в агропромисловому комплексі

У статті розглядається проблема визначення пріоритетів використання цифрових технологій на підприємствах агропромислового комплексу, зокрема у сфері рослинництва, в умовах обмеженості ресурсів, фінансів та кадрів. Сучасні сільськогосподарські підприємства стикаються з необхідністю підвищення ефективності своєї діяльності, що робить використання цифрових рішень дедалі актуальнішим. Однак в умовах обмежених ресурсів та браку досвіду впровадження таких технологій важливим стає вибір пріоритетних напрямів для їх реалізації.

Авторами запропоновано використовувати методологію нечітких експертних оцінок, засновану на використанні лінгвістичних змінних. Такий підхід дозволяє врахувати невизначеності та неоднозначності, характерні для початкових етапів цифровізації агропромислового комплексу. Експертна група, яка складалася зі спеціалістів у галузі сільського господарства та цифрових технологій, була залучена для оцінки найбільш перспективних напрямів впровадження цифрових рішень. За допомогою методів теорії нечітких множин були оброблені результати експертних оцінок, що дозволило об'єктивно визначити пріоритети цифровізації.

За результатами дослідження встановлено, що з точки зору цілей використання цифрових технологій найвищі оцінки отримали такі напрями, як моніторинг і програмування *врожаю, інформатизація та створення цифрової моделі роботи агронома. Впровадження цих технологій дозволить суттєво покращити управління виробничими процесами, підвищити врожайність, а також забезпечити більш раціональне використання ресурсів і мінімізацію втрат.*

У результаті дослідження були визначені конкретні пріоритети впровадження цифрових технологій у рослинництві, які можуть принести значну користь агропромисловому сектору.

Ключові слова: *цифрові технології, експертні оцінки, лінгвістичні змінні, управлінські рішення, автономна інформаційна система управління, програмування підприємств.*

Problem solving. One of the key drivers of the overall development of a nation's economy, and particularly its agricultural sector, is the implementation of digital technologies. On farms, these technologies enable the maximization of resource efficiency by applying data-driven, step-by-step solutions based on extensive information flows in complex systems. The integration of digital tools leads to higher productivity while significantly reducing costs and environmental impact by allowing for more targeted use of fertilizers, machinery, and other resources. However, the adoption of digital technologies in agriculture remains limited, often advancing through a process of trial and error. This highlights the need for further development of both the economic and organizational frameworks to support the successful integration of such innovations into crop production.

A critical challenge in this process is establishing clear priorities for the implementation of digital technologies, given their vast variety. The range of available devices, software, and technologies is highly diverse and must be systematically organized and prioritized for effective use. It is practically unfeasible to implement digital solutions across all problem areas in a single region or within a single enterprise simultaneously. Therefore, identifying the most effective digital technologies that can deliver the highest impact at the early stages of farm digitalization is a pressing scientific and practical challenge.

Analysis of recent research and publications. Several researchers have employed expert opinion methodologies in their studies, including B.E. Hrabovetskyi, H.M. Hnatienko, and V.E. Snityuk. Key aspects of optimal corporate management have been explored in the works of V.K. Zbarskyi, V.I. Matsybori, V.V. Morosanova, and A.A. Roan. Meanwhile, discussions on the digital economy and its directions can be found in the publications of T.L. Mesenburg, V.V. Klochan, and M.F. Nettle. Given that the integration of digital technologies into agriculture is still in its nascent stages, their economic aspects have been sparsely studied. Most of the available data remains non-formalized, which makes the expert opinion method particularly relevant for such cases [1, p.43].

Consequently, the task of identifying the key areas for introducing digital agricultural technologies [2,3 p.122] hinges on expert evaluations of existing options [4 p.234]. Ranking the potential uses of digital technologies by application priority falls under the category of optimization problems in uncertain conditions [5 p.48, 6 p.64-68]. In instances where formalized quantitative data is insufficient, these problems are addressed not with traditional mathematical approaches (such as probability theory or optimal programming theory [7 p.130-134]), but with fuzzy expert assessments expressed in natural language, processed using fuzzy set theory and linguistic variable methods [3 p. 156].

Purpose of the article. The goal of this article is to tackle the issue of prioritizing the implementation of digital technologies on farms, particularly in crop production, amid financial, personnel, and resource constraints. Given the improbability of simultaneously introducing the full spectrum of digital technologies, it is essential to identify the most effective solutions that can enhance farm efficiency.

Presentation of the main material of the study. Identifying the key areas for implementing digital agricultural technologies involves several important steps: setting critical goals and objectives for their use, selecting the most efficient and reliable equipment suited to the agricultural sector, and determining the most rational organizational structures and mechanisms for facilitating their adoption.

One of the main advantages of using fuzzy sets is their ability to process a wide range of expert opinions expressed in natural language, such as terms like «highly effective», «ineffective», or «unacceptable». This enables the generation of a comprehensive evaluation of both the practicality and effectiveness of a particular digital agricultural technology. The evaluation is based on the function of a specific technology's membership within the fuzzy set of priority areas for effective implementation.

A fuzzy set A for any element X is defined by a membership function $\mu_A; X \to [0;1]$. The value belongs $\mu_A(X)$ to the interval and captures the degree of membership of the element X to the set A. In the case of a conventional crisp set, the membership degree of any element is either 0 or 1 (meaning an element can either belong to the set or not belong to it at all). However, in the case of a fuzzy set, the membership probability is assessed, for example, as 0.3, 0.5, or 0.8. This approach aligns more closely with the tasks of expert evaluation in poorly formalized cases where there is a lack of information [1, p. 76].

A fuzzy set is typically expressed as a collection of ordered pairs, with each pair consisting of elements X and their corresponding membership functions $\mu_A(X)$. An example of a fuzzy set notation is as follows: $A = \{(x_1, 0.1), (x_2, 0.5), (x_3, 0.4)\}$.

To work with fuzzy sets, various mathematical tools such as U-shaped and S-shaped fuzzy numbers are utilized to process data and derive precise evaluations. These fuzzy numbers serve as a mathematical representation of expert judgments, translated into a formalized mathematical language. Specifically, triangular membership functions can be defined by expression (1):

$$\mu_A(x; a, b, c) = \begin{Bmatrix} 0, \ x \leq a \\ \frac{x-a}{b-a}, \ a \leq x \leq b \\ \frac{c-x}{c-b}, \ b \leq c \leq x \\ 0, \ c \leq x \end{Bmatrix} \quad (1)$$

where a, b, and c are large real numbers $a \leq b \leq c$. that correspond to the combined S-shaped functions of the functions F associated with them, represented in the following manner (2):

$$f_{x1}(x, a, b) = \begin{Bmatrix} 0, \ x < a \\ \frac{1}{2} + \frac{1}{2} cos\left(\frac{x-b}{b-a}\sigma\right), \ a \leq x \leq b \\ 1, \ x > b \end{Bmatrix} \quad (2)$$

Expert judgments articulated in natural language enable the construction of membership functions. In this process, each expert selects a linguistic term that reflects their assessment of the effectiveness of the technology being evaluated. The set of linguistic variables, denoted as A(X), is expressed as follows: A(X)={high, very high, fairly high, relatively high, above average, average, relatively low, fairly low, low, almost very low}.

This approach illustrates how fuzzy sets can be utilized to formalize and generalize vague verbal information, allowing for a more comprehensive and precise aggregation of informal expert opinions. It facilitates the transition from a series of qualitative assessments to a quantitative ranking of the efficiency and priority of digital technologies.

To form the expert group, a total of 13 experts were selected, as research indicates that a panel of 12-13 individuals achieves over 80% accuracy in results. Increasing the number of experts beyond this point does not substantially enhance the accuracy of the assessment and may even diminish the average level of competence due to the limited pool of specialists focused on digital technologies within the agro-industrial sector. The distribution of experts by professional background is as follows: five individuals from management and specialist roles within agricultural enterprises; three from specialized organizations that provide services related to digital technologies; three officials involved in the development of the agro-industrial sector; and two academic and pedagogical professionals.

For each category of digital agricultural technologies applicable to crop production, experts evaluated their effectiveness in the Kherson region using a linguistic scale. The scale is defined as follows: A(X)={very high efficiency, high efficiency, moderate efficiency, average efficiency, low efficiency}.

For instance, when assessing the efficiency of autonomous technologies (classified by their degree of localization), the results of the expert survey were recorded (Table 1). These findings indicate that experts perceive the effectiveness of autonomous technologies to be relatively low. Several key factors contribute to this assessment: autonomous devices that are not integrated into a cohesive control system tend to produce only marginal results in practice. Based on the data gathered, a spline function graph was constructed, which serves to evaluate whether these technologies can be classified as highly efficient.

Table 1

Example of expert assessment of the efficiency of autonomous technologies

Linguistic characteristics (fuzzy assessment) of the technology	Low efficiency	Moderate efficiency	Average efficiency	High efficiency	Very high efficiency
Number of expert responses in the interval	6	2	4	1	0
Share of responses in the interval	0,4615	0,1538	0,3077	0,0769	0,0000
Total number of responses	6	9	10	13	13
Cumulative share of responses	0,4615	0,6923	0,7692	1,0000	1,0000

The figure illustrates spline-functional diagrams that encapsulate the final evaluations made by experts regarding the effectiveness of digital agricultural technologies across three classifications: purpose of application, equipment utilized, and degree of localization (denoted as 1-3). Specifically, Figure 1 depicts the efficiency of digital precision agriculture technologies, differentiated by their level of detail. The graph presents monotonically increasing spline functions that demonstrate the cumulative value of the membership measure throughout the transition.

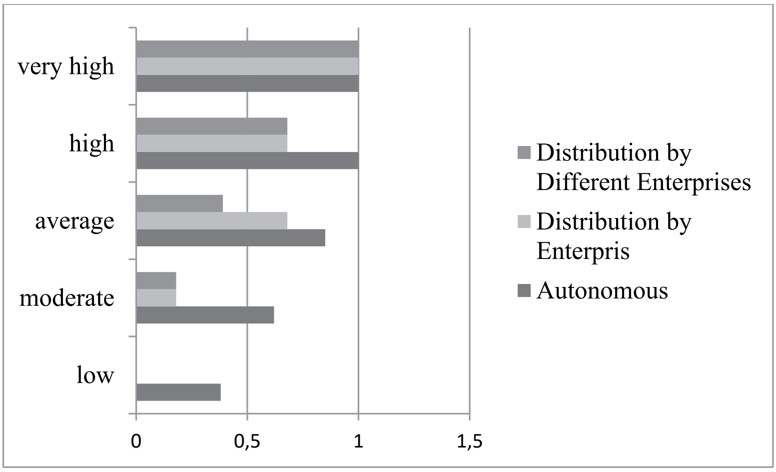

Fig. 1. Results of Expert Assessment of the Efficiency of Digital Agricultural Technologies Based on the Classification of «Location»

The significance of the transition in the middle of the horizontal axis inversely correlates with the efficiency rating assigned to the corresponding technology by experts. As illustrated in Fig.2, autonomous digital technologies receive an «average» efficiency rating or lower in 84% of assessments. In contrast, digital technology divisions achieve this rating in only 38% of cases. However, more than 60% of expert evaluations confidently indicate that these technologies are rated as highly efficient or even exceptionally efficient. Additionally, the ranking of technologies, derived from expert assessments, reveals that the most efficient technologies are those employed by large farms, whereas the least efficient are found within single-company autonomous farms.

Additionally, all agricultural technologies can be implemented following the principles of collective usage. Therefore, the primary values associated with the implementation of digital technologies, as evaluated by experts, can be categorized as either distributed within a single company or across multiple companies.

Let's examine the ranking of agricultural technologies based on their purpose (Fig. 2).

The data presented clearly indicates that experts have considered and ranked the following technologies according to the membership measure at the transition point:

1. Analysis, evaluation, and feedback technologies.
2. Information generation technologies.
3. Modeling and productivity programming technologies.
4. Decision-making technologies and precise agricultural interventions.
5. Management technologies for agricultural enterprises.

The ranking of these agricultural technologies by purpose is influenced by the operational conditions, as higher efficiency is achieved through the systematic digitalization of all facets of an agricultural company's operations. However, the assessments provided indicate that the initial digitalization priorities for crop production should focus on informatization, monitoring, and programming of crops-essentially creating a digital model of the agronomist's work. In this scenario, decision-making can still be performed «manually» and the application of targeted impact technologies may remain localized. Therefore, the expert assessment of application becomes particularly intriguing when overlaid with the results of the technology ranking (Fig. 3).

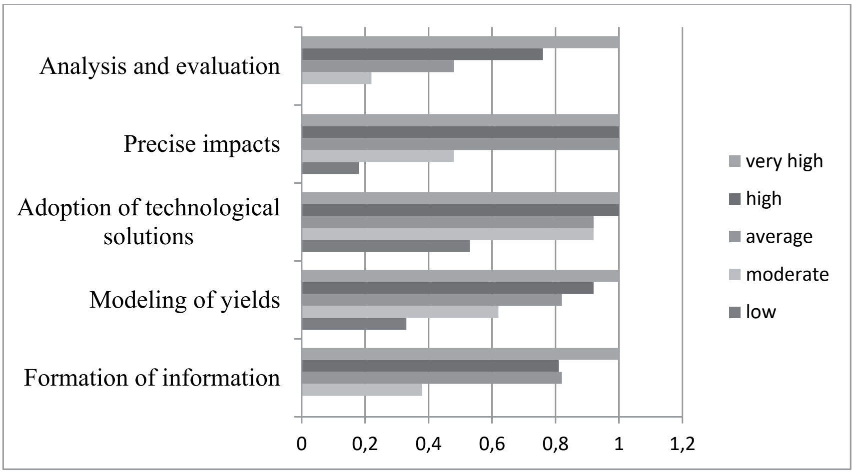

Fig. 2. Results of the Expert Assessment of the Efficiency of Digital Agricultural Technologies Based on the Classification of «Purpose»

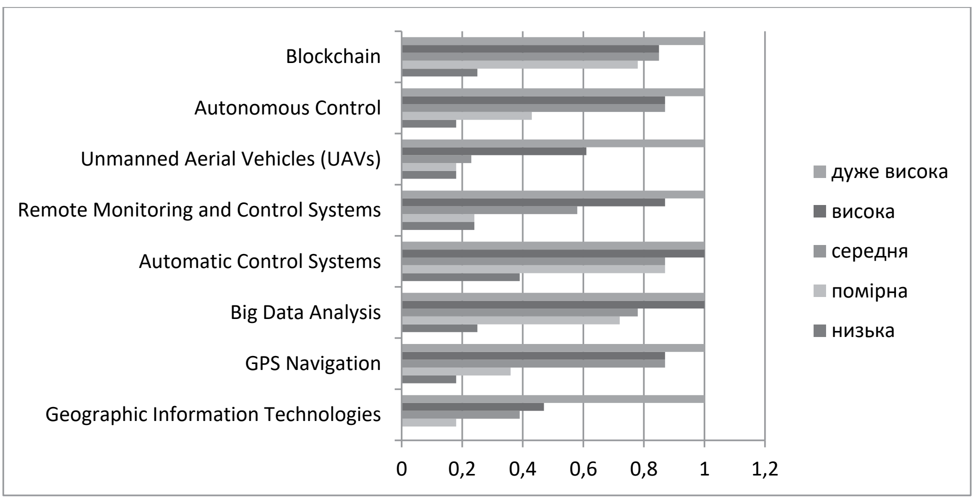

Fig. 3. Results of the Expert Assessment of the Efficiency of Digital Agricultural Technologies Based on the Classification of «Applied Devices»

It is important to note that certain peripheral and under-researched digital technologies, such as virtual and augmented reality as agricultural tools, were excluded from the expert assessment. Accurate evaluation of these technologies is challenging due to the practical uncertainties surrounding them.

The results of the expert assessment reveal a clear differentiation among digital agricultural technologies, as illustrated in the graph. Technologies currently recognized for their high efficiency in the region-approximately 50% or more of expert opinions classify them as high or very high in effectiveness-include: remote monitoring and control systems, technologies for the collective use of common pool resources, autonomous control technologies for ground equipment, geoinformation technologies, unmanned aerial vehicles, and agricultural aircraft. These technologies should be prioritized for implementation.

Conversely, technologies assessed as having relatively low efficiency, with over 70% of expert evaluations rating them as average or below, include automatic control systems, blockchain, sensors, big data analytics, and satellite navigation. As previously stated, the maximum benefits of digitalization are achieved through the integrated application of various technologies. Therefore, it is essential to utilize all or most of these technologies in crop production moving forward. However, during the initial training phase, especially under conditions of significant resource constraints, efforts should focus on the most effective technologies that promise the greatest returns.

Conclusions. This study conducted an expert assessment to evaluate the effectiveness and prioritize key areas for the implementation of digital technologies specifically tailored for crop production in the Kherson region. As a result, the following areas were identified:

1. Tools for Collective Use and Shared Access: Enhancing collaboration through the provision of shared digital resources and technologies.
2. Monitoring and Analysis Technologies: Implementing technologies for assessing the condition of plantings and crops.
3. Geographic Information Systems (GIS): Expanding the utilization of GIS to enhance decision-making processes.
4. Yield Programming: Developing advanced techniques for yield forecasting and management.
5. Digital Accounting and Control Systems: Establishing comprehensive systems for financial and operational management.
6. Unmanned Agricultural Ground Equipment: Integrating autonomous machinery for increased efficiency in farming operations.
7. Unmanned Aerial Vehicles (UAVs): Employing drones to address various agricultural challenges.

Based on these findings, it is recommended to initiate steps toward the digitalization of crop production at the foundational stage. The expert assessments reveal the following priority areas for the implementation of digital technologies in crop production:

1. Establishment and Promotion of Collaborative Institutions: Creating and ensuring the effective operation of organizations and platforms that support collective access to digital technologies, including the necessary equipment, specialized software, and computing resources.
2. Widespread Adoption of Monitoring Technologies: Promoting the mass implementation of technologies that monitor and analyze agricultural land and crops, particularly through the extensive use of unmanned aerial vehicles.
3. Enhanced Information Development: Continuing to gather detailed information on field conditions, vegetation, terrain, and other critical data necessary for crop production within current and future GIS frameworks. This will broaden the application of geographic information technologies by regional agricultural producers.
4. Dissemination of Yield Programming Technologies: Promoting and replicating complex yield programming systems that facilitate the partial automation of decision-making and operational execution.
5. Implementation of Digital Accounting Systems: Introducing digital systems for logistics and production process control, ensuring physical security, and optimizing resource conservation in agricultural enterprises.

6. Initiation of Autonomous Equipment Projects: Launching, expanding, and replicating projects that utilize unmanned agricultural ground equipment in regions where digital models of agricultural producers are already established and significant workloads are managed.

7. Expansion of UAV Applications: Replicating successful projects and broadening the application of unmanned aerial vehicles for agricultural tasks, including data collection and specific agro-technological interventions.

It is important to acknowledge that progress in some of these areas has already commenced; however, further expansion and replication are necessary. The first, fourth, and fifth areas are currently underrepresented in practice and must essentially be developed from the ground up. Notably, the fifth area–automated control and accounting-appears to be a feasible implementation for agricultural producers themselves. Evidence from domestic management practices indicates that various technological tools designed for monitoring property safety and personnel behavior hold considerable interest for enterprises.

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