Precision Phytotechnology in the Agro-industrial Complex

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Abstract: The application of advanced plant-based technologies to optimize agriculture productivity, sustainability and crop resilience is referred to as precision phytotechnology. The use of cutting-edge tools such as genomics and associated bioinformatics, microbial biotechnology, remote sensing and the use of AI-driven data acquisition and analysis helps understand and enhance crop performance, improve resource efficiency and mitigate environmental impacts due to climate change. In this review, the principles of functioning and methods of using information support of biocenology (study of biotic communities), principles of development of phytology (plant science), its phyto-productology (plant natural product research), reductive efficiency of soil microbiota of phyto-cenoses (plant communities) are highlighted. The theory and practice of phyto-cenoses production in Ukraine, the hardware and software of precision phyto-technologies used and their realization methods, are summarized along with materials on environmental aspects of application of precision phyto-technology and their efficient use. The review is designed for managers of agro-consulting companies managing commercial agriculture, graduate students, and researchers in the field of plant production.

Keywords: Phytocenosis, Precision agriculture, Phytotechnology, Agricultural productivity.

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1 Introduction

In recent years, information phytotechnologies, including cultural phytotechnologies and their information agriculture, have been gaining popularity. The aim is to support sustainable production of a wide range and optimum high-quality safe phytoproducts based on environmental principles and economic justification. Global climate change and other environmental challenges demand new strategies for advancing life sciences research. These strategies should support sustainable ecosystems in both urban and rural areas, particularly their plant communities and water bodies. This approach can be achieved in three stages: theoretical justification, education and research, and application in production and business.

In the developing countries of the world, information technologies based on the use of satellite navigation systems, computer software, technical vision systems, new types of automated machines, etc. are becoming particularly widespread [1-3] as technology and technical skills advance. There is a need to develop new principles for the formation and functioning of natural, human-made (anthropogenic), and cultural ecosystems, as well as their self-regulating biogeocenoses (which are ecological units consisting of interacting communities of organisms and their physical environment), using complex ecological and interacting community based information technologies. In recent years, researchers at the Institute of Agroecology and Nature Management of the National Academy of Sciences of Ukraine and the National University of Life and Environmental Sciences of Ukraine have started such studies in both theory and practice.

Information phytotechnology is a system for obtaining continuous information about the state of phyto-productive diversity of ecosystems, their associated biodiversity, and modeling the laws of optimal control of phytocoenoses, as well as the introduction of technological materials that affect the optimization of plant growth and development. An analysis of the development of the agro-industrial complex in different countries shows that several areas of ecosystem management are being developed in them, which differ significantly from each other primarily in terms of parameters such as economic, energy and environmental inputs. In particular, these areas can be logically divided into such groups as the production of phytoproducts with the use of synthetic preparations (extensive and intensive farming) and without their use (natural or biological or organic and biodynamic farming).

In recent years, efforts have focused on identifying promising production areas supported by modern technical and information technologies, such as no-till farming, precision farming systems (PFS), and information phyto-technologies (IP), including the information farming system (IFS). In our opinion, the production of phytoproducts from cultivated phytocoenoses should include several key elements such as 1) organizational and technological, 2) legal, certification and standardization, 3) cultivation of raw materials under different farming systems, 4) storage and transportation of raw materials, 5) processing of raw materials and 6) production of high-quality and safe products, 7) transportation and storage of products, 8) product sales, and product consumption. The principles of plant protection, include the control of economically damaging (harmful) and beneficial (useful) biodiversity that is directly or indirectly related to crops, raw materials or products, which play an important role in all stages of production. It is based on these principles that it is logical to consider biodiversity control in a single technological process of phytoproducts production.

Among these production stages, special attention should be paid to the development of laws for growing crops under different farming systems with justification in its unified technological process of controlling the biodiversity of agroecosystems. It should be emphasized that the literature contains many, and in some cases controversial, principles for classifying farming systems. For example, some authors [4-6] mention the existence of several areas of alternative farming such as, organic, biodynamic, biointensive mini-farming, low-cost sustainable farming, and ecological farming.

It is well known that crop yields depend on a complex of factors such as soil type, nutrient availability, water balance, climate, as well as plant requirements for soil structure and nutrients, heat, aeration, protection from pests and diseases. Therefore, the problem of building crop models is extremely complex and multifaceted, and more so in the current global climatic changes. In production and research activities related to the cultivation of crops and production of plant products, the question arises of the expected level and volume of such products in a certain area, i.e., the yield potential. The scientific study of this issue dates back to the 19th century and has a long history [7].

2 Problem Formulation

The phytomicrobiome (or Phytocoenoses), is a subsystem of biotic communities interacting with biogeochemical components of the environment, and are formed by a relatively stable grouping of plant organisms, of one or many generations, occupying specific geographic locations and maintaining close ties with its other components, including microbial communities [8]. In natural environments, biotic communities particularly plant-microbial systems

(PMS), develop within soils as part of the phytomicrobiome [9, 10]. Microbial communities (or microbial cenosis) is considered to be the largest unit of classification of microbial communities in the biological systems hierarchy. Although considered as a lower-ranking system within a higher-ranking biogeocycle system, it would be appropriate to refer to it as an open biological system of the super-organizational level [11]. It belongs to the class of highly complex systems, where the connections between elements are less rigid than in deterministic systems. A microbiome shows systemic features such as high mobility, changing ratios of components, and behavior governed by statistical patterns [12, 13].

Agriculture microbiome (Agribiocenosis) is characterized by low ecological reliability because agribiocenosis is not able to self-regenerate and self-regulate, but rather cause increased productivity during favorable agriculture conditions [11]. The basis of agro-microbiome depends on environmental factors, genotypes of the plants cultivated (agrophytocenosis), which are artificial plant communities formed on the basis of agrotechnical measures in agricultural landscapes.

While agriculture on land is well developed and reasonably well understood, researchers in Ukraine are paying particular attention to experiments on the development of technologies for the creation of advanced life support systems for space crews. One of the methods is by creating microgravity in the research greenhouse as experienced in the universal docking module of an International Space Station. However, as of today, technologies for cultivating a number of crops on artificial non-renewable substrates for growing plant vitamin products for crew members have only been developed. The development of methods to increase the service life of greenhouse chambers for growing plants without replacing the artificial non-renewable substrates will require the development of productive plant microbial systems in microgravity conditions. This has to be accomplished while ensuring that the three main processes that create the phenomenon of life on Earth: photosynthesis, nitrogen fixation and mineralization are effectively maintained. Thus, a set of individual features is not enough for the formation of effective plant microbial systems; it is important to search for systemic criteria, morphological and functional changes in cells that characterize the adaptive and productive features of plant microbial systems associated with their strategies of life in natural and artificial environments.

Researchers can avail of clues to study microgravity using classic examples of legume/mycorrhizal symbiosis, since one of the most studied plant-microbe interactions. In the symbiotic system between nodule bacteria and legumes, nitrogen fixation represents the most ecologically important process. Legumes increase the amount of nitrogen available to plants and, indirectly, ensure the preservation of carbon in the soil as part of mineralized plant biomass [7, 11]. It has been shown that most nitrogen is stored in the rhizosphere of plants [14], microbial biomass [15], and as organic matter [16]. However, recently, more attention has been paid to the study of biological mechanisms of nitrogen transfer to deep soil layers and the impact of these processes on global changes of the nitrogen cycle in nature [17], and in the role of soil microbial communities in regulating nitrogen turnover [18]. For example, Orwin et al. [19] showed that fast-growing plant species in interaction with microbial complexes contribute to the enhancement of mineralization processes and increase soil nitrogen losses through denitrification processes. According to the authors, fast-growing plant species had the capability to increase the volume of denitrification due to their influence on the denitrifying microorganismal community. In contrast, slow-growing plants with high nitrogen-use efficiency reduce soil nitrogen availability, promoting the development of microbial communities dominated by micromycetes. Mycorrhizal fungi are known to play a role in plant nitrogen uptake. In nitrogen-limited systems, certain micromycetes can establish direct transport pathways from organic matter to the plant, enabling it to bypass the inorganic nitrogen cycle and thereby reducing nitrogen losses [19].

Other possible ways of solving the problem of forming effective plant-microbial systems include increasing plant resistance to climate change [20], water deficit conditions [21], and leveraging mycorrhiza's ability to boost plant resilience under limited water availability in the rhizosphere. Some researchers [22] have shown a direct link between the composition of soil food chains and ecosystem processes. It was based on the formation of microbial cenoses, where a large microbial biomass creates a network of energy channels made up of micromycetes and bacterial components. In our opinion, the formation of a relatively stable spatial organization of the rhizosphere microbiota can help reduce nitrogen and carbon losses in the soil.

The control of the species composition of vegetation within floodplain pastures, or the use of intercropping (growing two or more crops in the same field), may have additional benefits for stabilizing ecosystem processes, such as nitrogen conservation and crop production in drought conditions. For example, the presence of more drought-tolerant plant species could reduce the impact of such disruptions on protein metabolism and yield loss [23].

In addition to these direct effects, plants can indirectly affect nitrogen metabolism through their ability to influence microbial cenosis and change the physical and chemical properties of the soil, including the content of phosphorus and sulfur compounds [24]. Phosphorus enters the root system of plants in the form of orthophosphoric acid anions ($H^2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) [25]. All phosphorus transformations in the body are associated with the addition or transfer of phosphoric acid residues, i.e., phosphorylation or transphosphorylation. Phosphorylated molecules of sugars, organic acids and other compounds can transfer phosphoric acid residues to other substances. Subsequently, in the process of substrate, oxidative and photosynthetic phosphorylation, the cell's energy compounds, ATP, are formed. ATP is a source of energy for most cellular life, and hence, phosphorus deficiency affects all processes in the cell. This means that phosphorus is not reduced in cells, and in all compounds, it is only in the oxidized form.

Plants absorb sulfur from the soil in the form of sulfate SO_4^{2-}. Sulfate can accumulate in the roots and shoots in an unreduced form, but in order to incorporate sulfur into organic compounds, it must be reduced to sulfide. Sulfate reduction occurs mainly in chloroplasts and requires photosynthetic products such as ATP and reduced ferredoxin. The process of sulfate reduction begins with the activation of inert sulfate. The process is carried out with the help of ATP in the presence of magnesium ions. These are some of the key distinctions between phosphorus transformations and those of nitrogen or sulfur.

Therefore, by maintaining a high level of microbial activity in the rhizosphere, the plant can largely coordinate the activity of nitrogen and phosphorus cycling processes and ensure the supply and assimilation of nutrients transformed into readily available mineral compounds.

Despite the fact that there are many methods for stimulating soil microbiota, most of them are not taken into account in ecosystem control methods. The study of the relationships in the plant-soil microbiota system is necessary in the development of methods to ensure the most efficient movement of nutrients in the rhizosphere soil. In this context, soil and vegetation sensing can be performed using both remote sensing and proximal sensing. In such technologies, sensors are used for various purposes, including the study of quantitative spatial and temporal changes in plants and soils. Currently, advances in electronics development allow us to quickly receive clear signals that can be used to create special recommendations for an information site. It is now possible to create broad-spectrum measurement systems based on new principles and approaches and deploy them in the field.

The proximity sensors operate while the equipment moves across the study landscape, measuring indicators, analyzing the data, and generating a large amount of information about soil properties. This information can be recorded along with geographic coordinates for future geospatial data processing, such as in maps or programs. Generally, "on-the-go" sensors can be moved across the field using a tractor, all-terrain vehicle, pickup planter, sprayer, or in a combine and combination. Such systems can record yields, crops and soil properties, as well as field elevation using high-precision Global Navigation Satellite System (GNSS) receivers.

Crops grown are another indicator of soil characteristics that interact with agro-climatic conditions and agricultural practices. Monitoring vegetation cover is crucial for the early detection and mitigation of stresses. During the growing season of corn, researchers have used remote sensing to study plant biomass using calibrated color positive and color infrared images to predict the nutrient requirements [26].

According to modern requirements, crop yield management is correlated with the result of spatial and temporal changes in the rhizosphere microbiota of the soil associated with variations in the physical, chemical, and biological properties [27]. The biodiversity of bacterial communities depend on the type of soil and its texture [28].

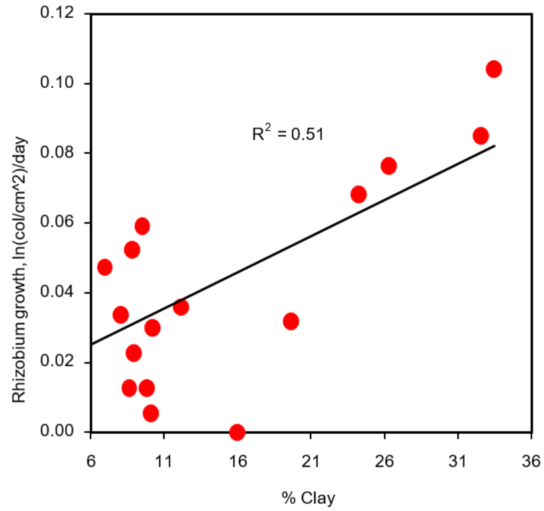
Special sensors can be used to monitor and map the soil, and the information obtained from them was correlated with the data on the spatial heterogeneity of the soil microbiota content, using the approach described in [29]. Soil biota processes soil organic matter, and residual degradation is involved in nutrient cycling and contributes to the stability of soil structure

[30]. Therefore, in our opinion, it can be considered as indicators of soil quality based on the results of microorganisms' adaptation to environmental changes, such as stress from water shortage or root hypoxia due to flooding, lack of congenial substrates, presence of pollutants, the speed of response of plant-microbial systems to the application of soil management methods and land use practices.

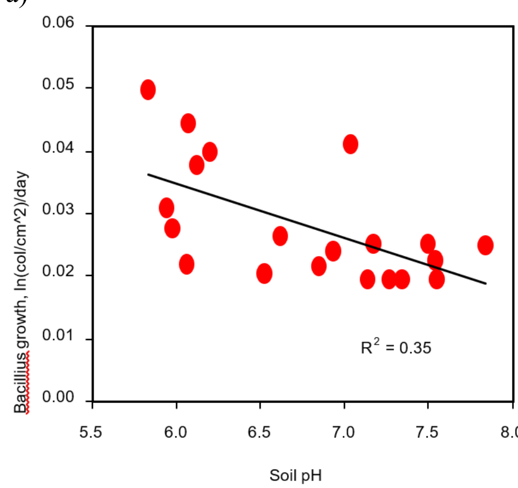
Our proposed scheme for studying the formation of effective plant-microbial systems was used to develop new approaches to the modern scientific field of soil bio-sensitivity. To achieve this goal, we developed a spatio-temporal model of plant–microbial system architecture, providing a framework for understanding the spatial variability of soil microbiota and supporting the development of improved soil management strategies. Despite the relative limitation of the analysis of colony growth rates, symbiotic and associated microorganisms with soil characteristics and photosynthetic activity of plants, the figures to correlate rhizosphere microbiota development with physicochemical parameters of soil samples and plant vegetative index can be generated.

The above suggested method for example can be used to check the presence of *Bacillus* and *Pseudomonas* bacteria in a biofilm and the correlation with soil pH and buffer pH. The content of *Pseudomonas* in the biofilm and the correlation with the quantitative content of K, Ca, Mg, and Al elements in the soil and a correlation between clay content and the presence of *Rhizobium* in the samples, all suggest symbiotic partnership within a given soil microbe population. It is known that population formation of the genus *Rhizobium* depends on the rhizosphere architecture of the macro-symbiont [31, 32]. A slope of the growth curve for diazotrophic bacteria such as *Rhizobium* and *Bacillus*, at a range of sample sites can be calculated as a correlation with physical (clay content) and chemical (acidity) soil properties as shown in Fig. 1a and 1b.

To determine the Excess Green Vegetation Index (E+xG) of experimental plants, we propose using proximal digital imaging of sampling points in the VIS–NIR range, specifically the visible (520–590 nm), near-infrared (630–685 nm), and red-edge (705–745 nm) bands, to calculate the vegetation index at selected field locations. A relationship was identified between plant vegetation index values (Excess Green) and soil electrical conductivity (Fig. 2a), as well as between Excess Green and soil organic matter content (Fig. 2b).

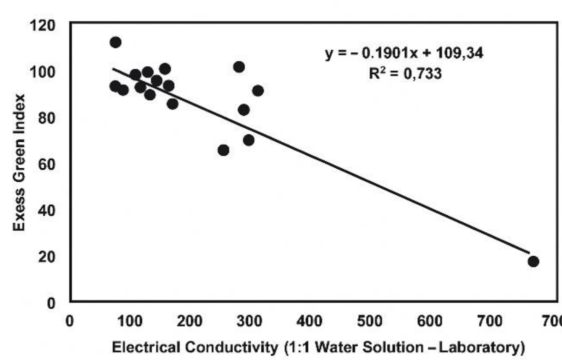


a)

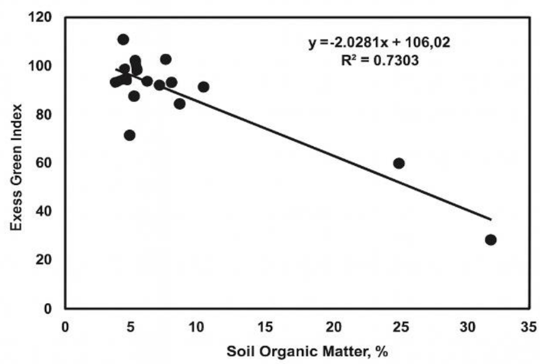


b)

Fig.1 a) Regression model of *Rhizobium* growth in soil with different percentages of clay content; b) Regression model of *Bacillus* in increasing soil pH.



a)



b)

Fig.2 Regression models of excess green plant vegetation index based on bacteria development with soil physicochemical properties, a) on electrical conductivity, and b) on increasing soil organic matter percentage.

3 Problem Solution

Currently, non-destructive optical methods are widely used for objective assessment of the physiological state of plants [32], since, most of the existing methods do not allow to trace the dynamics of optical properties of photosynthetic and intracellular structures of the leaf. They are also difficult to implement in a compact rapid diagnostic system for determining the current state of plants.

Stationary spectroscopy methods were originally used in studies of whole photosynthetic cells and chloroplasts, in order to gain more accurate and differentiated information about the complexity of the photosynthetic apparatus by increasing the spectral resolution and combining different types of spectroscopic measurements [33]. This approach revealed the heterogeneity of the organization of the chloroplast pigment system due to the existence of native forms of chlorophylls that interact with each other in the process of energy transfer. Native forms of chlorophyll are pigment-pigment interacting groups of molecules that are held in close spatial proximity to one another. Further studies of the spectral characteristics of chlorophyll in the cell in comparison with the calculated model systems have allowed us to form an idea of the existence of aggregated forms of chlorophylls in vivo [34]. The data on the study of the anisotropy of the spectral characteristics of the pigment system of the photosynthetic apparatus obtained on whole objects with the interpretation of the spatial location of native forms are known [35]. The traditional method involves the extraction of individual pigment-protein complexes from chloroplasts, determination of their biochemical composition, spectral and photochemical properties [36]. However, it has significant disadvantages associated with damage to native forms of chlorophyll and pigment-protein complexes (PPC) during their release. A theoretical analysis of the peculiarities of energy transfer in heterogeneous systems of photosynthetic cells has proven that by the spectral studies method of organizing photo-membranes, energy stabilization at photochemical centers can be achieve. And various theoretical models of the arrangement of pigment forms can be also be calculated [37].

Studies on whole cells and chloroplasts established key principles for the organization of the photosynthetic pigment system. These principles include, a) energy heterogeneity, where photosynthetic cells contain a whole set of different native pigment forms, each with distinct energy properties, b) substantiation of its functioning in order to confirm and explain the system, and how energy is transferred in a specific, non-random direction, and c) finally the role of pigment-pigment interaction, where chlorophyll molecules interact with one another, which is crucial for organizing these native pigment forms [37-40].

A frequently employed technique involves studying the kinetics of optical characteristics in plant tissue by analyzing backscattering indices. This approach allows researchers to concurrently investigate the kinetics of integral scattering intensity and determine the dynamic changes in the concentrations of various structural elements within the leaf mesophyll, treating the leaf as a complex optical and biological system. Depending on the external conditions, the leaf mesophyll changes the morphology of assimilation tissues, geometric cell sizes, content and ratio of chlorophylls and carotenoids. Consequently, leaf blade tissues are optically heterogeneous media, where the Monte Carlo method is used to estimate the absorption coefficient. This allows for comparing the spectrometry results with modeling results and data from other authors [41]. In existing publications, the complex mathematical model of leaf blade morphology were simplified, and only flat mesophyll layers were considered in areas without venation and surface villi. The inner layers were combined into one with averaging of optical parameters, since these layers were believed to make little contribution to backscattering.

For example, the shape of the spectral reflectance curves of leaves in the "red edge" region is very sensitive to the chlorophyll content [42-43]. A quantitative indicator of these changes can be the ratio of the intensities of the two main maxima in the graph of the 1st derivative (I2/I1), located in the intervals of 722-725 nm and 700-705 nm. Using this regularity, we have obtained linear and nonlinear regression equations for calculating the pigment content based on spectral characteristics. Along with the 1st derivative method, a principal component method was developed that allows for a quick estimate of chlorophyll content in the case of incomplete projective coverage with high accuracy of spectral measurements. The spectral reflectance curves of vegetation in the visible range can be used to test such important parameters as the supply of nitrogen nutrition to plants [44-45].

There are different approaches to using vegetation indices based on sensor measurements and calculating them using algorithms to determine the Nitrogen Sufficiency Index (NSI), as previously mentioned. Some nitrogen application rates are described by algorithms recommended for use to achieve the potential yield determined by the methodology. Biomass estimation is carried out on the day of the probe. Several additional Indy-CES vegetation indices are used to calculate the N status of soybean and wheat plants using an active sensor to measure the Green Normalized Difference of Vegetation Index (GNDVI).

An example, the interaction between water and nitrogen stress in plants was shown in a vegetation experiment with maize plants in the field based on remote sensing studies, where the width of the main spectral band was used to calculate various indices (standardized water supply variation index [NDWI], and nitrogen index [NRI]). The authors established that water and nitrogen compounds were efficiently absorbed in wheat plants, and crop yields increased at optimal nitrogen application rates (100-120 kg N ha^{-1}). There are other examples of the use of vegetation indices to detect water stress, determine chlorophyll content, and assess the primary productivity of the field.

Associated with nitrogen is the formation of symbiotic nitrogen-fixing plant-microbial systems with legumes and in the stability of the soil microbiota composition [46]. To study the processes of growth and development in plant-bacterial systems, a method has been developed that can be used to study the architectonics of microbial cenoses associated with the root system of plants in natural and artificial environments. The determination of plant vegetation indices have allowed us to assess the activity of the photosynthesis process, during which the physical energy of photons is converted into chemical energy ATP and reducing metabolic intermediates (NADPH), which are used for the synthesis of carbohydrates and nitrogen-containing assimilates. These in turn, become the starting material for the synthesis of biochemical components of cells, tissues and organs, determining the functioning of plant-microbial systems. These represent a qualitatively new approach to precision agriculture and are at the initial stage of development in Ukraine in terms of research and production.

For the first time, this area began to be theoretically substantiated in 2004 at the National Agrarian University at the Department of Agricultural Mechanization (Prof. L.V. Aniskevych). From the point of view of controlling the phytosanitary state of ecosystems, the staff of the Department of Integrated Plant Protection and Quarantine (Assoc. Prof. S. Vyhera) began to conduct substantiation and research in alignment with this department. At the present stage, the following definition of information farming is the most logical.

Information agriculture is a system of obtaining continuous information about the agro-biological state of ecosystems in space and time, and modeling the laws of optimal management of biological resources and technological materials to produce high-quality and safe phytoproducts based on environmental, social and economic requirements [1,2] according to L.V. Aniskevich and S.M. Vyhera.

The results of recent studies have shown that it is necessary to implement methods for optimal control of natural and cultural ecosystems, especially biological resources, and the introduction of technological materials. This raises the need to develop new theoretical and practical approaches to ecosystem management, based on the analysis of continuous information about the state of bioresources and the environment in space and time, to ensure their highly efficient functioning, both for obtaining high-quality and safe phytoproducts and for phyto-designing.

The above thoughts once again confirm the idea that at the present stage it is necessary to apply a system of information farming based on the coordinate principle, the basic features of which are:

- continuity of the process of monitoring agricultural land;
- control of the agro-biological potential of the field in the optimal mode due to the coordinate principle;

- precise control (in time and space) of the dynamics of the number of harmful and beneficial biodiversity of agroecosystems;
- performance of crop harvesting operations in the mode of variable technological parameters;
- full control of product quality and safety;
- rational profitability without negative impact on the environment;
- and LCA analysis for better farming and production management

A distinctive feature of the information farming system is the presence of a model for optimal management of the agro-biological potential of the field. The input signals of the model are locally determined field data obtained on the basis of continuous monitoring of phytocoenoses, and the output of the model is control signals that determine the law of optimal management, which is implemented by the same services as in the directive method.

The goal of information agriculture (IA) technology is to quickly generate, intermediately process, and transfer current reliable localized information about the agro-biological state of the field to the database of the agronomist's automated workstation (AWS) in order to manage crop production in an optimal mode. To perform work on monitoring locally defined parameters, it is necessary to create a new class of agricultural machines - field information machines (FIM), especially unmanned field information machines (UFIM). These technical means can be ground-, air-, and space-based.

The constituent elements of the natural and technical system of the unmanned robotic complex for monitoring localized parameters are: the field itself; a subsystem of mobile information robots (recorders) for collecting, accumulating and transmitting information; a control room for monitoring and remote control of the FIM; a center for maintenance and storage of the FIM; an automated workstation of an agronomist (agronomist's workstation) with a database of locally defined data; technical means for delivery, servicing and evacuation of the FIM to the maintenance center. Among these components, the FIM subsystem is the most important, as it is designed to collect locally determined data on the agro-biological state of the field and serves as the basis for managing the agro-biological potential of the field in an optimal mode (Table 1).

Such approaches are extremely necessary at the present stage due to the incorrect regulation of agrochemicals in some cases, their uneven application within the agro-biocenosis, unreasonable economic costs, and significant environmental pollution during plant cultivation. The new crop production strategy allows us to significantly reduce the economic costs of technological materials, their standardization, and improve the environment. In the future, leveraging precision agriculture, information phytotechnology, and information agriculture will allow us to create novel biocenoses and agro-biocenoses, giving us the ability to systematically and effectively fine-tune their natural regulatory mechanisms.

4 Future directions

The next era of precision phytotechnologies will merge artificial intelligence, robotics, and advanced biological science to create farming systems that nurture each plant as a unique entity while sustaining the planet. Fields of the future will be cultivated by swarms of autonomous drones and robots that sense, analyze, and act with millisecond precision, delivering individualized care for water, nutrients, and protection while eliminating the waste of broad-spectrum chemical use. Edge computing will enable these systems to think and respond instantly in the field, while multi-omics data fusion—integrating genomics, phenomics, soil health, and environment—will unlock unprecedented insights to guide precision breeding, biostimulant use, and even phytoremediation for ecosystem restoration. Farms will evolve into living digital twins, simulating climate impacts, pest outbreaks, and soil changes in advance, empowering farmers with predictive, climate-resilient strategies. By embracing regenerative agriculture and phytocenosis principles, AI will orchestrate complex intercropping systems that enhance biodiversity, restore soils, and close nutrient cycles. Blockchain-enabled transparency will link every stage of production to consumers and regulators, ensuring food systems that are not only more productive, but profoundly sustainable, resilient, and restorative—ushering in a new paradigm of personalized agriculture designed in harmony with nature.

5 Conclusions

The concept of precision phytotechnology integrates the authors' thirty years of research, contributions from colleagues at the National University of Life and Environmental Sciences of Ukraine and other research institutions, as well as the practical expertise of leading farms in the country. Artificial intelligence (AI)–driven precision farming is reshaping agriculture by combining remote sensing, machine learning, and big data analytics to optimize crop production. Data generated from satellites, drones, and smartphone applications enable the detection and monitoring of plant diseases, nutrient deficiencies, and pest infestations. Deep learning models, for instance, can identify leaf discoloration patterns to diagnose diseases such as powdery mildew or rust in wheat. Incorporating advanced phyto-technologies and applying the principles of phytocenosis into agricultural practices fosters sustainability and resilience, which are critical to addressing the challenges of climate change.

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Table. Current hardware and software applications in precision phytotechnology

Category	Hardware	Software / Algorithms	Applications
Remote Sensing	Satellites (e.g., Sentinel-2, Landsat-8) Drones (UAVs with multispectral, hyperspectral, thermal sensors) Smartphone-based imaging devices	Image processing software - ENVI [47], ERDAS Imagine [48], Pix4D [49], Agisoft Metashape [50] AI-based disease detection apps	Monitoring vegetation indices (NDVI, ExG), disease detection, crop stress mapping, yield forecasting
Field-based Sensors	Soil moisture probes, EC meters, pH sensors IoT-enabled wireless sensor networks Ground-based hyperspectral cameras	Sensor data platforms – LabVIEW [51], MATLAB [52], R [53], Python-based analytics [54], cloud IoT dashboards	Real-time soil condition monitoring, nutrient mapping, irrigation scheduling
Farm Machinery	GPS-guided tractors and sprayers Variable-rate applicators Robotic planters and weeders	Precision agriculture platforms - John Deere Operations Center [55], Trimble Ag Software [56], Climate FieldView [57]	Site-specific seeding, fertilization, and pest control
AI & Machine Learning	High-performance computing clusters Edge devices for real-time processing	Deep learning frameworks - TensorFlow [58], PyTorch [59], Keras [60] Machine learning libraries - Scikit-learn [61], XGBoost [62]	Plant disease detection, phenotyping, predictive modeling, yield estimation
Big Data & Cloud Systems	Cloud servers (AWS, Google Cloud, Microsoft Azure) Local data loggers	Data integration platforms (QGIS [63], ArcGIS [64], CropSyst [65], DSSAT [66] Big data analytics – Hadoop [67], Spark [68]	Data storage, geospatial mapping, decision support systems