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Intelligent control system for clonal micro-propagation of plants

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Abstract

The management of clonal micropropagation is an urgent topic in modern biotechnology and agriculture. This direction is a method of propagating plant materials based on the cloning of genetically identical plants. This process allows for the preservation and use of valuable plants without changing their genetic structure, ensuring high stability and quality of the material. The selection of an optimal nutrient medium for clonal micropropagation is one of the most important tasks faced by researchers and specialists in plant biotechnology. When selecting a nutrient medium, its optimal composition may depend on the specific genus, species, and variety of the plant, as well as on the stage of its development. To solve this problem, it is necessary to conduct research and determine the optimal conditions for a specific type of clonal micropropagation, which requires a lot of time and effort. For more effective selection and analysis of the nutrient medium, a clonal micropropagation management system is needed, which will offer the most suitable nutrient medium for a particular plant and analyze the dynamics of its growth from the selected nutrient medium. The purpose of this work is to develop an intelligent system of clonal micropropagation, where information about the plant, the nutrient medium, and the parameters of plant development act as input parameters. Within the framework of the article, the author focused on the consideration of the functional, informational, behavioral model, and the model of intelligent system components. Due to the implementation of these system models, the user has the opportunity to obtain information about the optimal nutrient medium for the selected plant, visualize plant development according to the specified data, as well as assess plant development according to the optimal and specified nutrient medium.

Keywords: Class diagram, Clonal micropropagation, Intelligent system, Nutrient medium system models, User interface.

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1. Introduction

Clonal micro-propagation plays a key role in modern agriculture. It is a method of reproducing plant materials based on the cloning of genetically identical plants. This method ensures the sustainable production of high-quality planting material, contributing to the conservation of biological diversity and the use of valuable plants without changing their genetic structure.

The selection of a nutrient medium is an important step in the clonal micro-propagation of plants, as it determines the success of growing embryos or cells and the formation of new plants. The nutrient medium must contain all the necessary macro- and microelements, vitamins, amino acids, and growth hormones required for the development and growth of plants. It must be optimally balanced to ensure proper absorption of nutrients and to provide optimal conditions for cell division and differentiation. Additionally, the nutrient medium must be sterile to prevent culture contamination by bacteria, fungi, and other microorganisms that can negatively affect plant development. The correct selection of the nutrient medium allows for optimal conditions for the successful reproduction of plants and the preservation of their genetic diversity [1].

The selection of an optimal nutrient medium is a complex and time-consuming process that requires consideration of many factors, such as species and varietal characteristics of plants, specific requirements of tissue culture, optimization of cultivation conditions, and the recreation of natural plant growth conditions [1]. The disparity of data and species and variety specificity make this process even more difficult. Thus, to optimize the processes of clonal micro-propagation of plants, an information system is needed that will automate and optimize the process of selecting a nutrient medium and contribute to the preservation of plant genetic diversity.

It should be noted that the introduction of information technologies into agricultural production management processes allows for the automation of work processes such as watering, fertilization, and lighting control; as well as the collection and analysis of data on plant growth and development. The listed capabilities of information technologies in solving agricultural problems emphasize the relevance of their implementation.

Currently, there is a clear trend towards the introduction of artificial intelligence methods in solving agricultural problems [2-9]. In the work of Sashina, et al. [7], the architecture of artificial intelligence for the information-measuring and control system of the aeroponic method of growing plants in an urban environment is proposed [7]. Additionally, scientists have proposed a specialized biosensor designed to monitor the biological composition of plants and their general condition to improve the efficiency of artificial intelligence algorithms. A 1×2 mm sensor can be implanted into the roots of control plants. This solution complements the information-measuring and control systems of the aeroponic method of growing plants in an urban environment, providing additional automation. In the work of Maslakov, et al. [5], approaches to solving the problem of accurate and objective registration and assessment of plant growth and development (of its individual parts) on nutrient media of different compositions and various stages of development, grown in vitro, were considered [5]. For the process of objective fixation of plant growth parameters, researchers have assembled a prototype of an automated system that takes photographs of plants, collects objective information about the morphometric parameters of plants during their growth, and evaluates the condition of plants based on the creation of their volumetric reconstruction.

An analysis of the literature on the research problem shows that there is a tendency to introduce intelligent systems into various agricultural tasks to increase production efficiency.

The purpose of this work is to design and implement an intelligent control system for clonal micro-reproduction of plants. This system is based on the analysis of existing architectures and principles of organization of agricultural systems.

The relevance of this development is due to the fact that intelligent systems available on the world market (KEGG, PhytoVision) solve the tasks of management accounting in crop cultivation or represent an information resource that introduces the user to relevant biological and medical knowledge. The KEGG system (Kyoto Encyclopedia of Genes and Genomes) is a web resource that provides access to a number of biological databases and tools for analyzing biological and medical data, created in 1995 as part of the Human Genome project. Since its creation, the KEGG integrated database has been significantly expanded and currently has sixteen databases, divided into four categories for ease of search: system information (data on metabolic pathways, gene modules, etc.), genomic information (data on individual genes, genomes of various organisms, orthologous groups), chemical information (data on chemical reactions occurring in living organisms), and information directly related to human health (data on human diseases, medicines, etc.). KEGG also provides a number of tools for convenient work with databases and analysis of the information stored in them. The PhytoVision system is designed to monitor plant growth to increase yields and reduce production costs. This program processes sensor readings, considering changes in plant weight caused by the removal of leaves, lateral shoots, and harvesting. In graphical form on a computer monitor, it displays the actual increase in green mass over a certain period of time. Moreover, the program calculates a growth model considering the expected weather conditions, which allows for predicting the arrival of the crop and planning the sales schedule more accurately. Thus, it becomes possible to manage the yield and optimize energy consumption.

An analysis of the literature on the research problem and the practice of selecting nutrient media by domestic specialists in the field of biotechnology indicates a contradiction between the need to implement an intelligent control system for clonal micro-propagation of plants and the lack of available tools for processing and analyzing information in the subject area under consideration. The revealed contradiction led to the need to develop the mentioned information system. The implementation of the system models proposed by the author of the article makes it possible to maintain the following database, which provides the ability to process the necessary set of entities, including family, genus, nutrient media, and phytohormone concentrations, as well as the selection of a nutrient medium, visualization of plant development, and conducting an intellectual analysis of available data.

2. Materials and Methods

The developed intelligent control system for clonal micro-propagation of plants will allow for the resolution of tasks faced by employees and managers of agricultural entities. This system has the following functionalities: viewing general information on plant families and genera, selecting the optimal nutrient medium for clonal micro-propagation of plants, and visualizing plant development while considering parameters such as plant height, number of nodes, and efficiency of root formation.

The input parameters include information about the plant, the nutrient medium, and the plant development parameters. The implemented functionalities of the system will enable reasonable management decisions in selecting the necessary nutrient medium for growing plants.

The development of an intelligent control system for clonal micro-propagation of plants is an important area of research that combines web development, data visualization, analysis, and forecasting technologies using various programming languages and tools.

The front-end part of the presented web development includes work with three main technologies:

1. HTML (HyperText Markup Language) is a markup language that defines the structure of a web page using tags. It tells the browser which elements are present on the page and establishes their relationships and locations.
2. CSS (Cascading Style Sheets) is used to set the appearance of HTML elements.
3. JavaScript is a programming language used to add interactivity to web pages. JavaScript has access to page and browser elements, allowing the creation of animations, handling user events, changing the page content dynamically, and much more. It is also responsible for the client-side business logic of web applications. A Chart.js library was used to visualize the data on the site.

The Python programming language, along with the NumPy and scikit-learn (sklearn) libraries, was used for data mining and predicting the callus formation coefficient. To ensure interaction with the MySQL database on the website, a backend was developed using the PHP programming language. PHP provides the ability to query the database, extract data, and dynamically generate content on web pages.

To manage the database, special software is used: a database management system, in particular, MySQL. It supports various operating systems due to its cross-platform nature.

To create the website, the Visual Studio Code editor was used, which is a popular text editor designed for creating and debugging modern web and cloud applications. The site code was run on the Apache web server, which handles HTTP requests to the site on a local server.

For easy switching between different versions of HTTP, MySQL, and PHP, a local Open Server was selected directly from the program. A local server allows running a website on a computer without the need for hosting, which facilitates development and testing. The local server emulates the operation of the real server of the host provider, converting the site into HTML code before displaying it in the browser.

The key points of this article are functional, informational, and behavioral models, as well as models of system components. The author analyzes scientific and technical literature and conference materials on the use of information systems to optimize the processes of clonal micro-propagation of plants. A critical analysis of both foreign and domestic literature on clonal micro-propagation of plants was also conducted. The authors of the study, using modeling notations such as UML, IDEF0, and DFD, presented functional, informational, and behavioral models, along with models of intelligent system components. This system automates the process of selecting a nutrient medium, where the user selects a plant species and a plant development parameter for visual display. The system executes a query to the database and, within a few seconds, provides information about the optimal nutrient media for the selected plant and visualizes the development of the plant according to the selected parameter.

3. Results and Discussion

Currently, there is an active introduction of intelligent systems into a number of business processes of business entities. This is due to the fact that they significantly improve the automation of business processes, providing higher efficiency, flexibility, and decision support. The ability to process and analyze data, as well as integrate with existing systems, makes them indispensable in modern business. These features are implemented using artificial intelligence technology, in particular, machine learning.

When implementing the information system, we put forward the following user requirements: the ability to study background information on families and genera, selection of a nutrient medium for a specific plant species, analysis of plant development according to growth parameters, as well as an assessment of the forecast of the nutrient medium effectiveness selected by the user.

During the implementation of the proposed system, the knowledge of biotechnological experts in the studied subject area was collected, which formed the basis for decision-making in the system, the formalization of this knowledge in the form of system models, including the data structure, algorithms for their processing, and the necessary infrastructure for the system's functioning.

The selection of a suitable nutrient medium for the cultivation of a particular plant is one of the most expensive items of expenditure in clonal micro-propagation. This process resembles research work because, despite the genetic identity of the cloned plants, each line may have unique nutritional needs.

Even if plants belong to the same species, their ability to interact with the environment may vary depending on the region of origin and genetic characteristics. Thus, a nutrient medium suitable for tree propagation in one region may be ineffective for a tree of the same species but with different genetics and metabolic processes. For some cloned plants, it may be necessary to develop a specialized nutrient medium that considers their unique characteristics and needs. This may include changes in the concentration of hormones, minerals, or other additives. Thus, optimization of the nutrient medium is an important and time-consuming step in clonal micro-propagation. One of the disadvantages of this approach to selecting a nutrient medium for cloned plants is the high risk of error due to the complexity and unpredictability of plant reactions to changes in the medium composition. In addition, this process may require a significant amount of time and effort to achieve optimal results. Nevertheless, fine-tuning the nutrient medium for cloned plants can significantly affect their growth, development, and overall productivity, making this process an integral part of research work in the field of biotechnology.

The analysis of the development of plants created using clonal micro-propagation is also an important and complex process that requires significant time and resources. An intelligent control system for clonal micro-propagation will allow biotechnologists to reduce the time for processing information, decrease the likelihood of errors, and improve the accuracy of results.

The diagram shown in Figure 1 illustrates how the user can interact with the intelligent control system of clonal micro-propagation. The actor of this diagram is the user. The options for using the system by the user are as follows:

1. Working with tools: selection of a nutrient medium, visualization of plant development, and intellectual analysis.
2. Information review: directory, system information, contact information, information about tools.

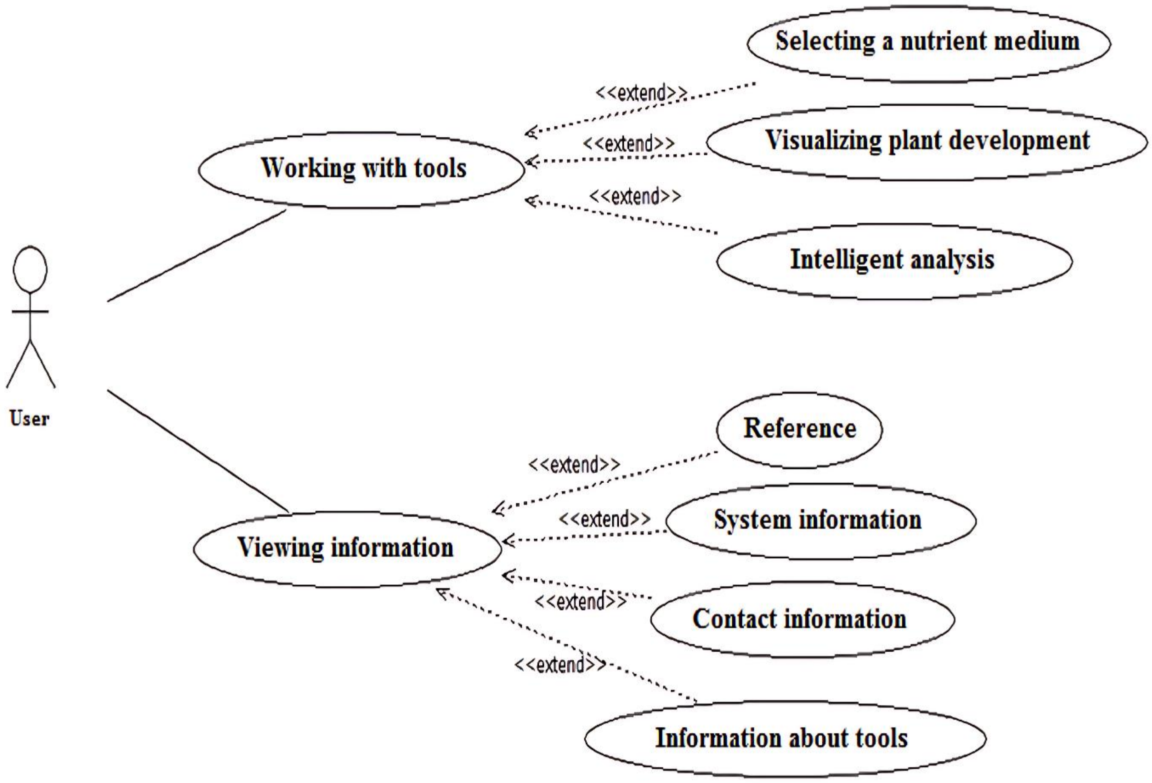

Figure 1.
Diagram of the user options of the system's use.

The information model of the system is displayed in a class diagram, which provides a graphical representation of the system's classes and their interactions, as well as attributes, methods, and relationships between classes (Figure 2).

There are classes in this diagram:

1. "Family" that includes the following operations:
    - Add indicator ();
    - Delete indicator ().
2. "Tribe" containing operations:
- Add indicator ();
- Delete indicator ().
3. "Species" that includes the following operations:
- Add indicator ();
- Delete indicator ().
4. "Optimal conditions", which includes the operation:
- define ().
5. "Mineral environment" with operations:
- add indicator ();
- delete indicator ().

6. "Hormonal environment", which includes the following operations:
- add indicator ();
- delete indicator ().

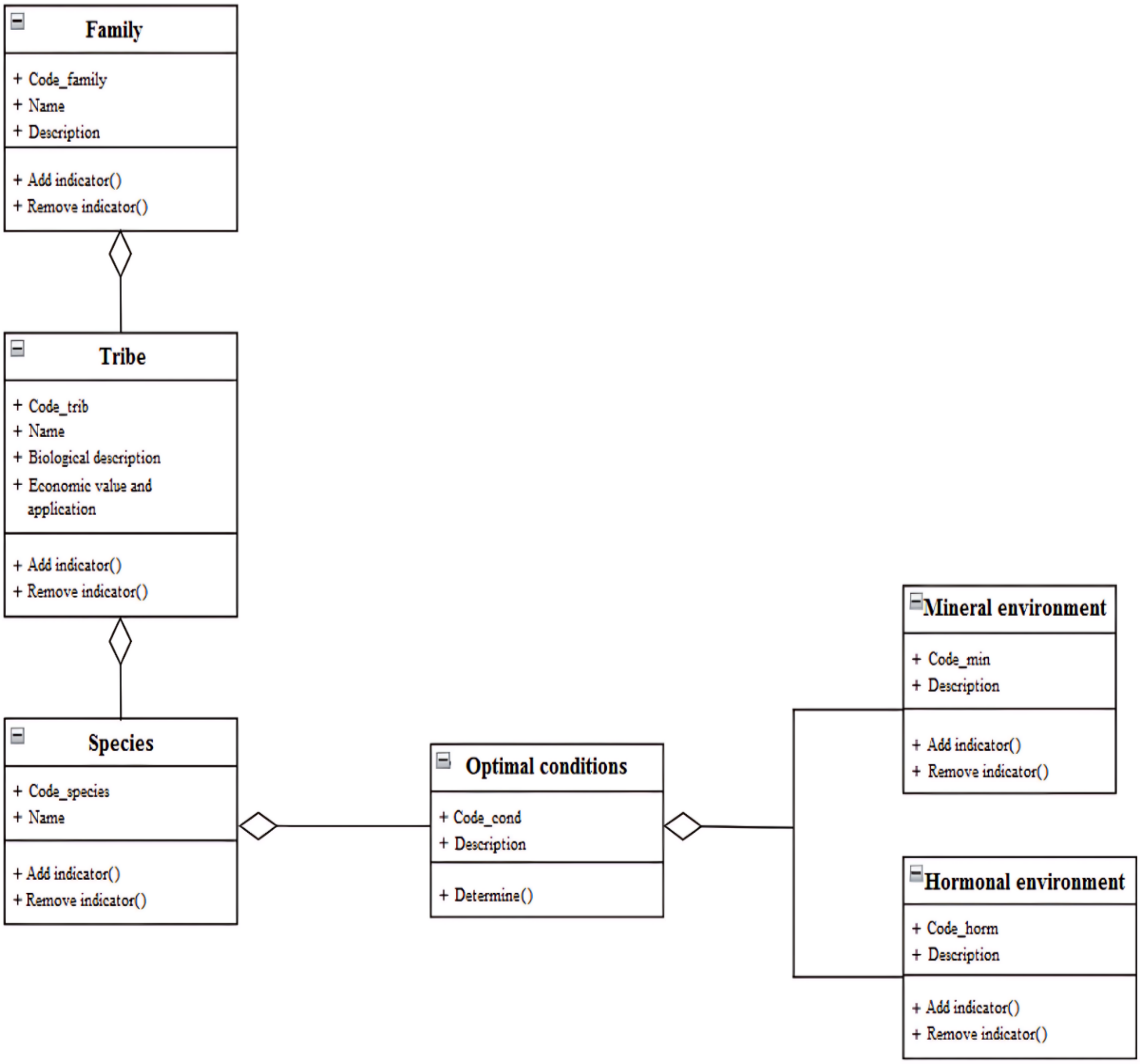

Figure 2.
Class diagram of the information management system for clonal micropropagation.

To implement the model of functional diagrams in IDF0 notation and data flow diagrams in DFD notation, the Ramus Educational structural design CASE tool was used. Figure 3 shows a contextual diagram describing how the entire system works.

The information system input receives:
- Analyze data regarding the plant.
- Analyze the information regarding the nutrient medium.
- Analyze the information regarding the plant development parameters.

Based on the results of processing the received data in the system, we obtain:
- Analyze the information on the optimal nutrient medium for the chosen plant.
- Visualization of plant development based on the entered data.
- Visualization of plant development according to the optimal and introduced nutrient media.

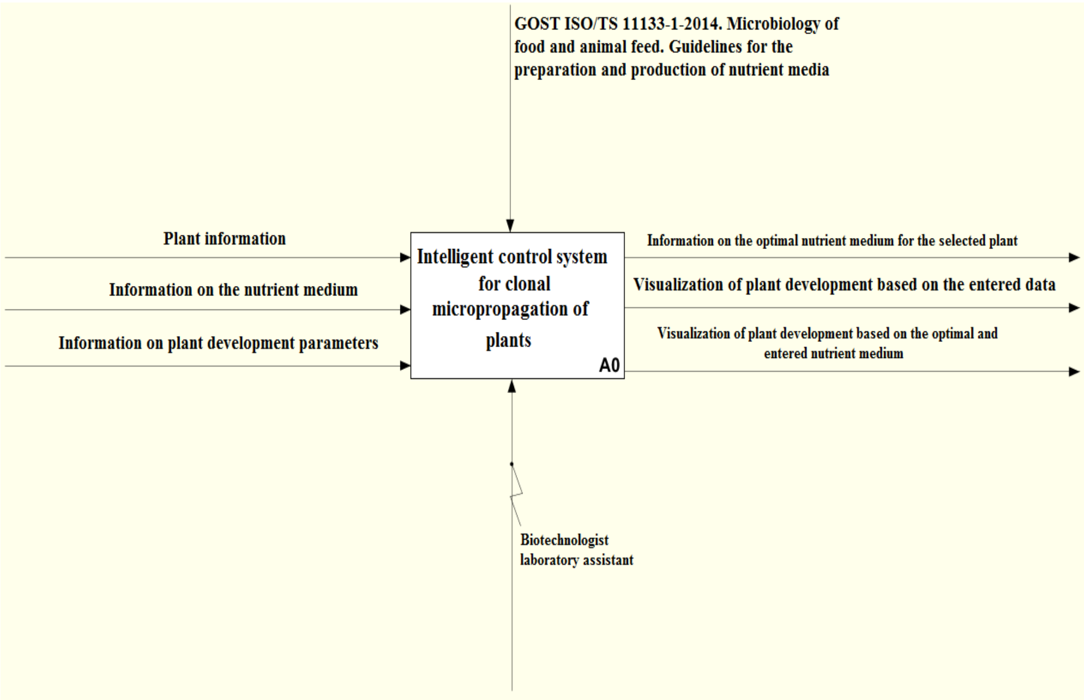

Figure 3.
Contextual diagram of the system.

Having decomposed the context diagram to determine the system sub-functions, three decomposition blocks can be distinguished:

- Analyze information: choosing a plant and its parameters.
- Selection of the nutrient medium.
- Analyze information on plant development analysis (Figure 4).

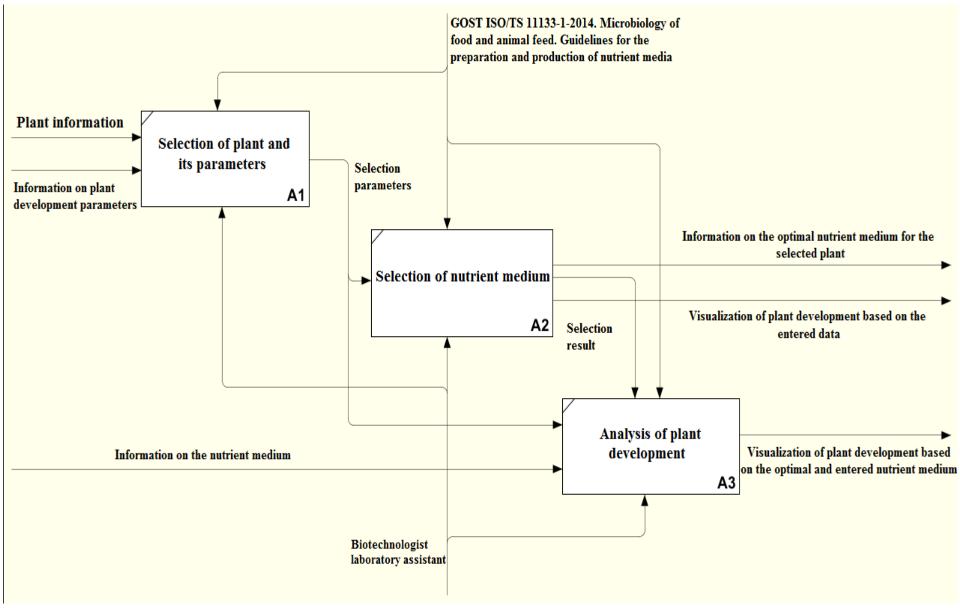

Figure 4.
Diagram of the system decomposition.

Let's consider the main features of the user interface of an intelligent control system for clonal micropropagation. The main page displays the logo, the site menu, and the name of the system, "Clonal Micropropagation Management System" (Figure 5). In the header of the page, there are menu buttons: Home, Directory, Tools, Contacts, and Log In.

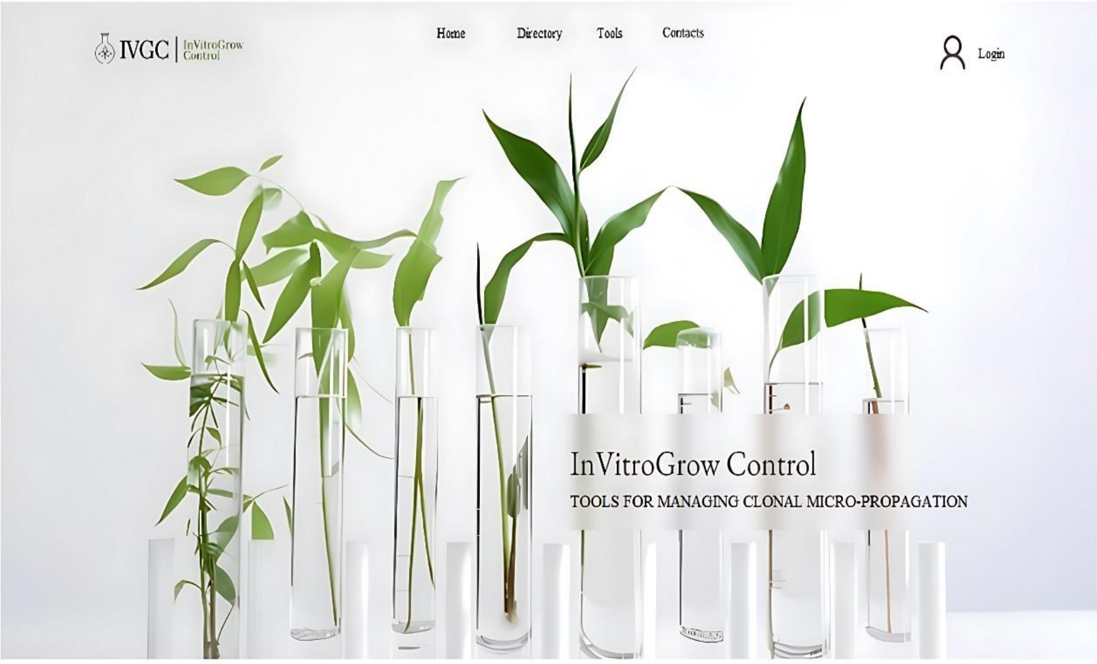

Figure 5.
Main page of the website.

Also, on the main page, you can find general information about the system and its capabilities, such as tools (selection of a nutrient medium, development analysis) and a reference book (search by family and species).

By clicking on the link in the Directory menu, the user can navigate to the directory page containing information on families and genera included in them. The page contains block elements characterizing individual families or genera. Each element has a sign indicating its belonging to a family or genus, a name, and a brief description (Figure 6).

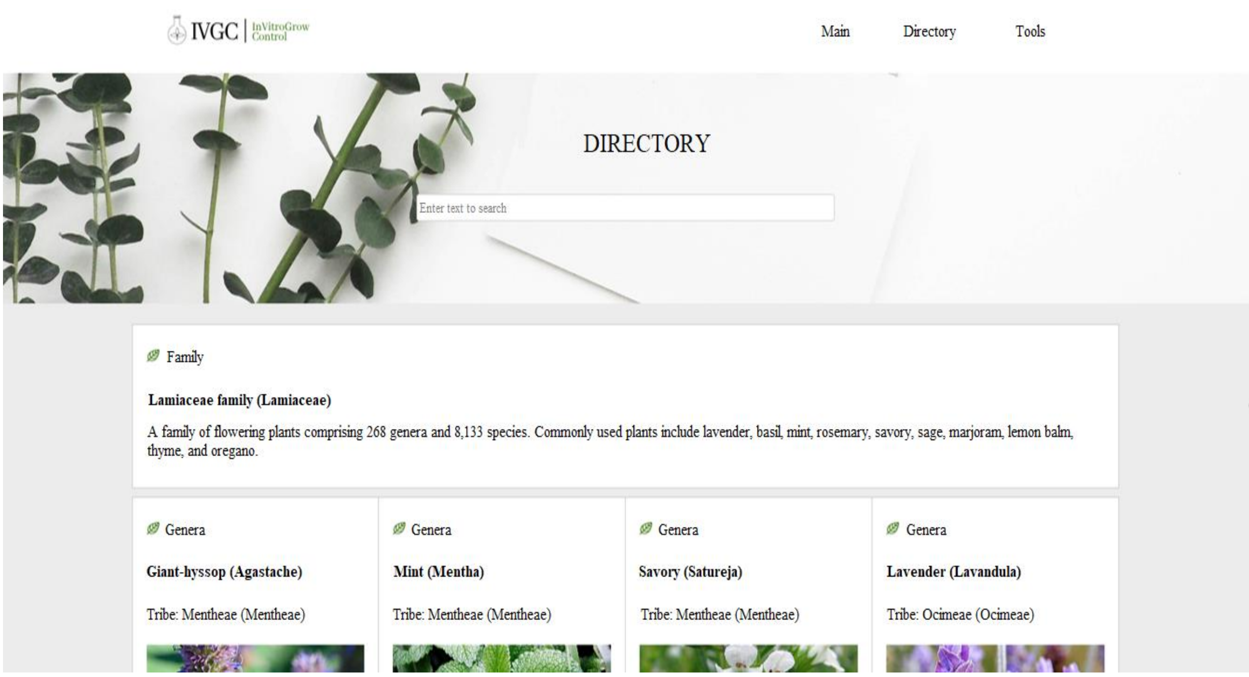

Figure 6.
System directory.

When you hover the mouse over the blocks of the directory page, they are highlighted in color, and they also allow navigation to the pages of a family or genus (Figure 7).

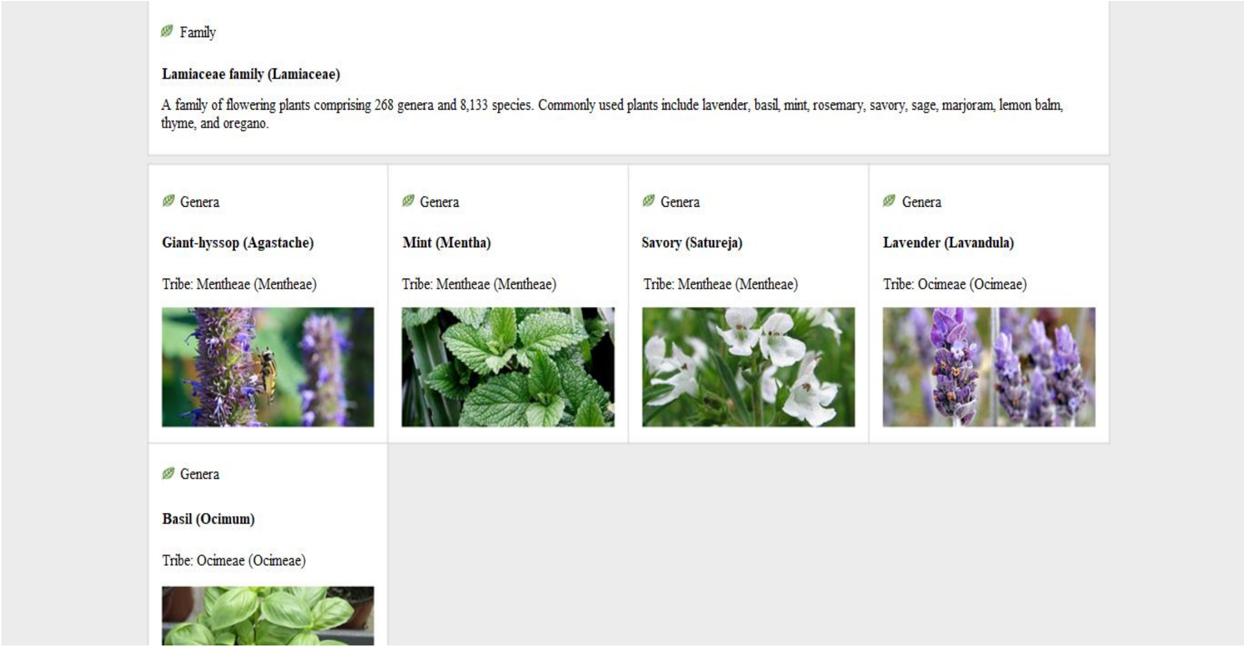

Figure 7.
Blocks of the directory page.

When you go to the family page, you can see the title with the family name, a brief description, and an image. Below is a panel with a reference that transfers to a certain part of the family characteristics (classification, synonyms, subfamilies) (Figure 8).

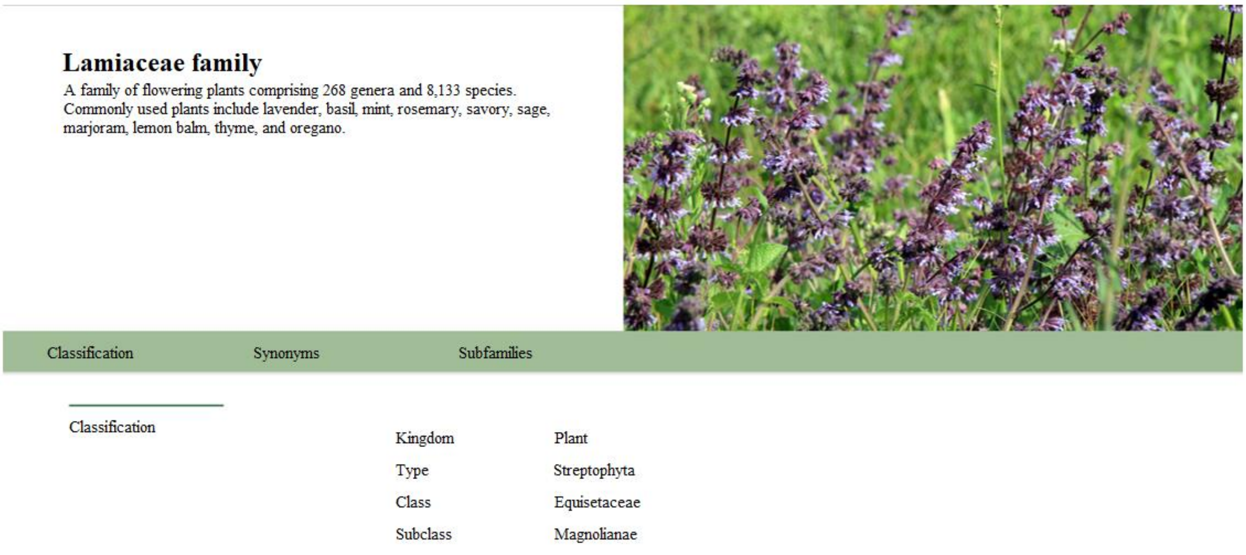

Figure 8.
Family page.

The page of the genus displays a title with its name, a brief description, and an image. Below is a panel with a reference that transfers to a certain part of the genus characteristics, which includes classification, synonyms, species, and distribution (Figure 9).

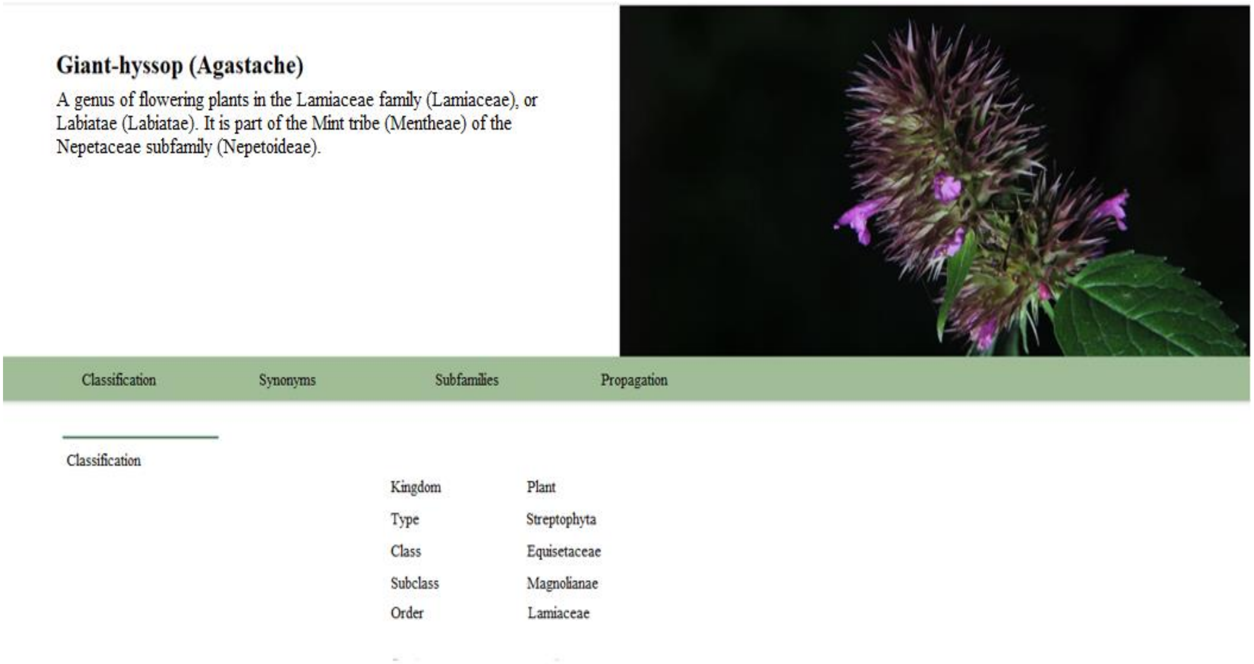

Figure 9.
Genus page.

An example of the description of the classification and synonyms of the genus Giant Hyssop is shown in Figure 10.

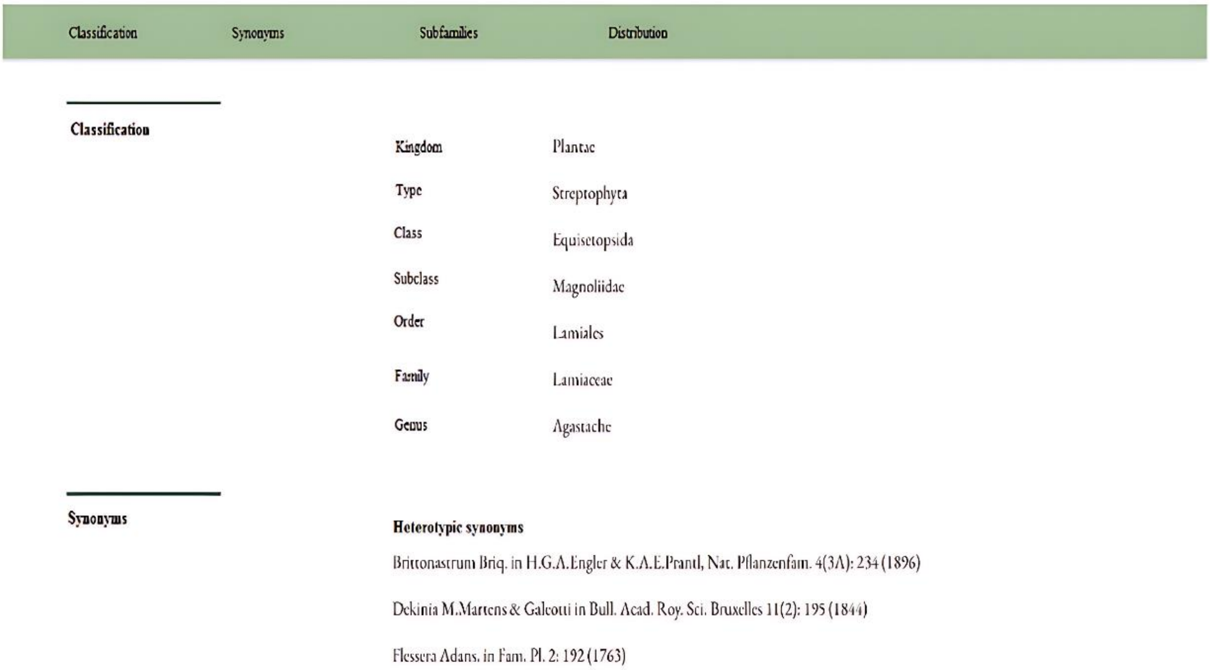

Figure 10.
Contents of the classification sections and synonyms of the genus Giant-hyssop.

The distribution of the plant genus can be viewed on the map. Thus, the distribution areas of the genus Giant Hyssop can be seen in Figure 11, where the natural distribution zones are shown in green and the invasive ones in purple.

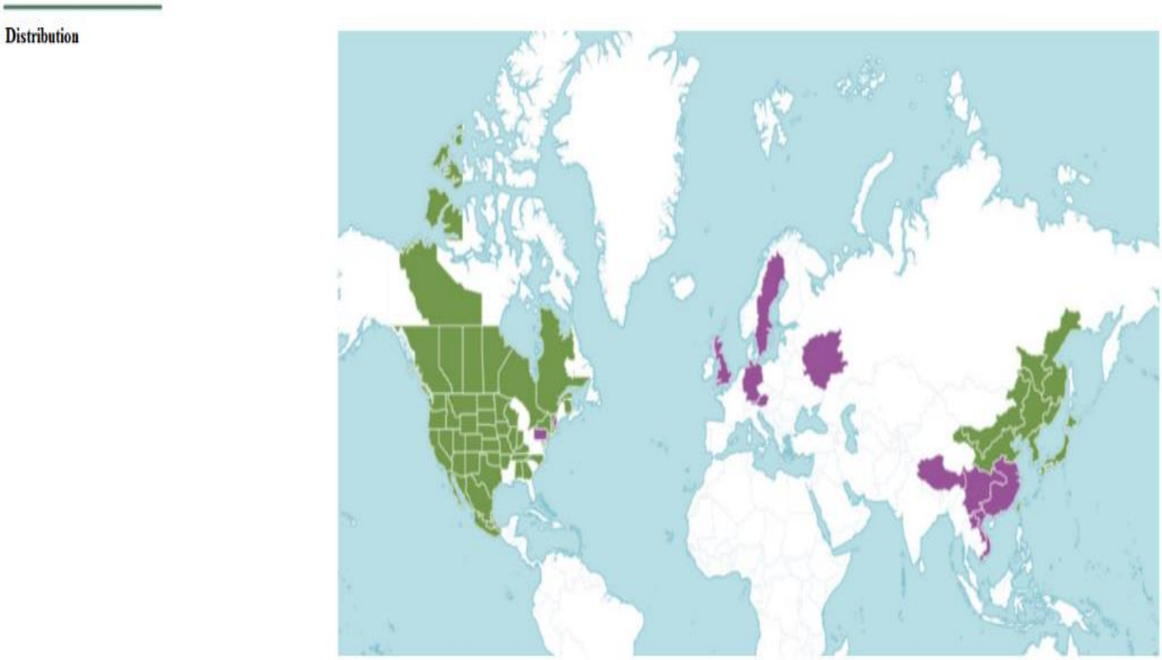

Figure 11.
Distribution of the genus Giant Hyssop.

In the menu of the webpage header, the "Tools" button provides a form where you can select a nutrient medium for a specific plant species (Figure 12).

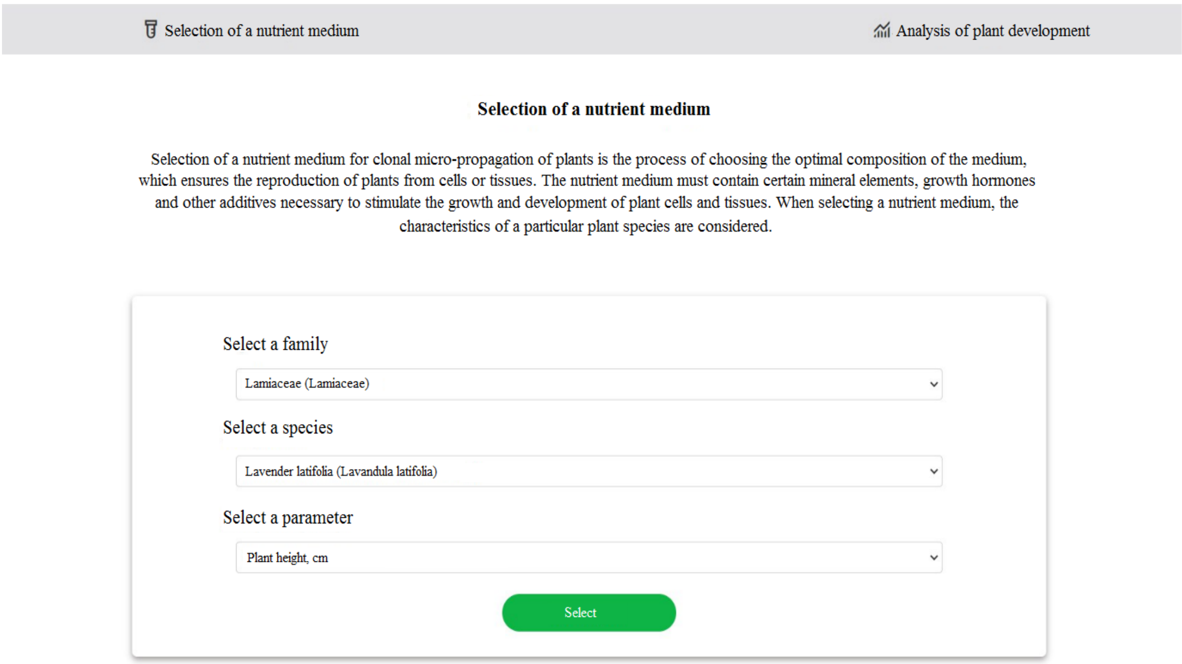

Figure 12.
The nutrient medium selection page.

The family and species of the plant of interest are chosen in the drop-down menus (Figure 13).

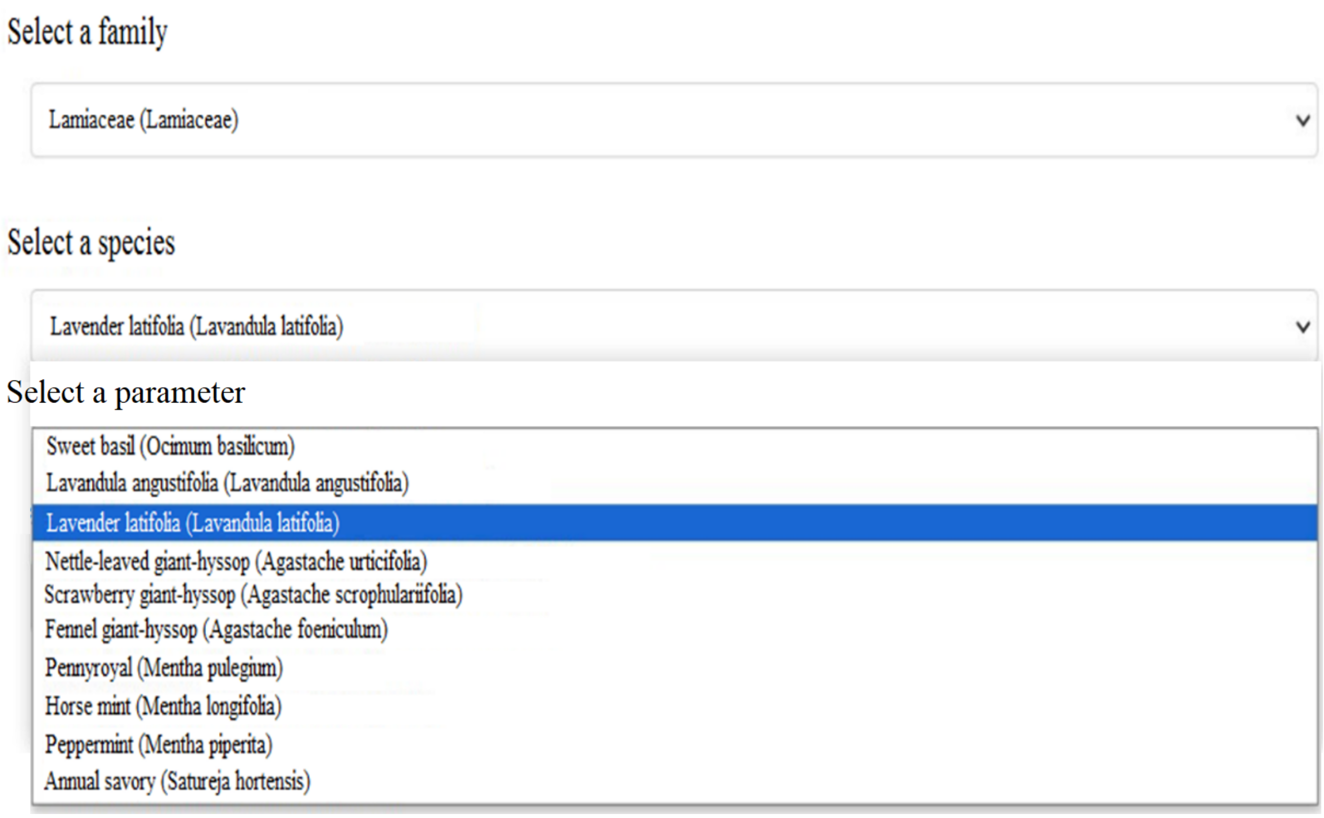

Figure 13.
Choosing the plant species.

You can also select the parameter by which data visualization will be performed: plant height, number of nodes, and root formation efficiency (Figure 14).

Figure 14.
Selection of the plant parameter for visualization.

After selecting all the necessary data, a table displaying various nutrient media compositions is presented in order of decreasing effectiveness. This table describes the names of the recommended nutrient media along with their mineral and hormonal compositions (Figure 15).

The optimal selection of nutrient medium was made for the species Lavender latifolia (Lavandula latifolia):

Name of nutrient medium	Recommended mineral composition	Recommended hormonal composition
MS0	Murashige-Skoog	-
MS10	Murashige-Skoog	1 mg/l BAP + 12 mg/l NUK
MS5	Murashige-Skoog	2 mg/l NUK + 0.2 mg/l Kinetin
MS7	Murashige-Skoog	0.5 mg/l BAP + 12 mg/l IMC
MS9	Murashige-Skoog	20 mg/l NUK + 2 mg/l Kinetin

Figure 15.
Recommended nutrient media.

It is also possible to obtain a graphical representation of nutrient media depending on their effect on plant growth with the selected parameter "plant height" (Figure 16).

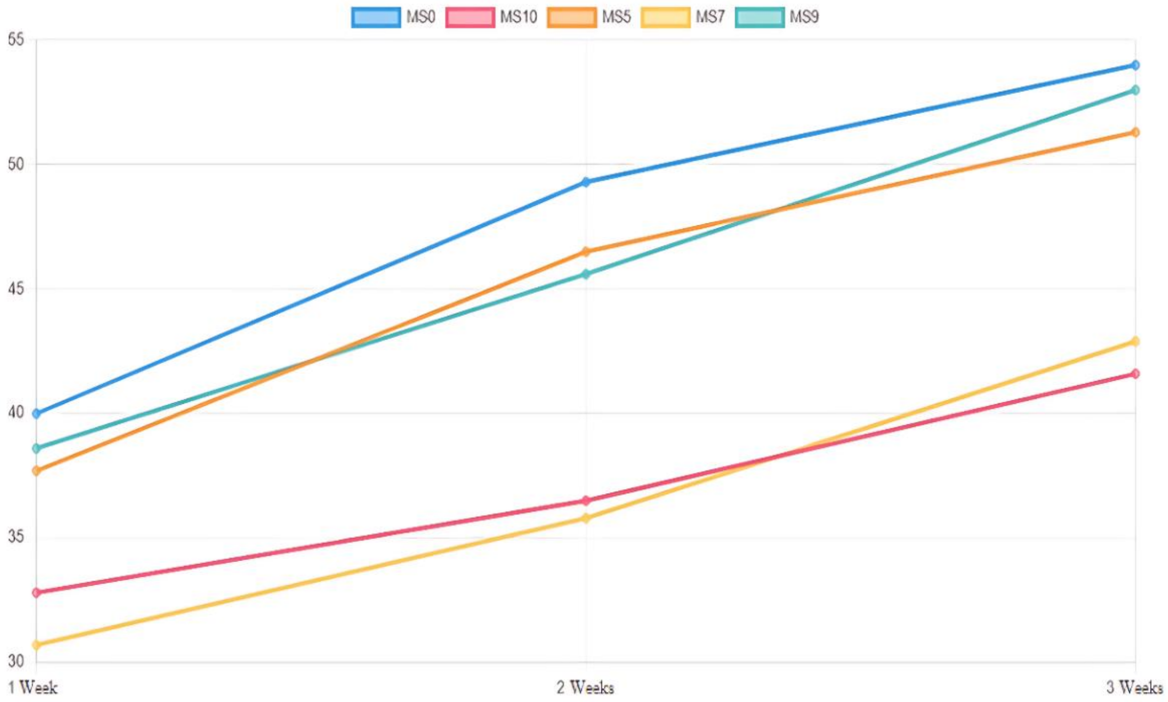

Figure 16.
"Plant height" parameter.

In this graphical representation, it is possible to sample nutrient media to hide indicators that are not of interest (Figure 17).

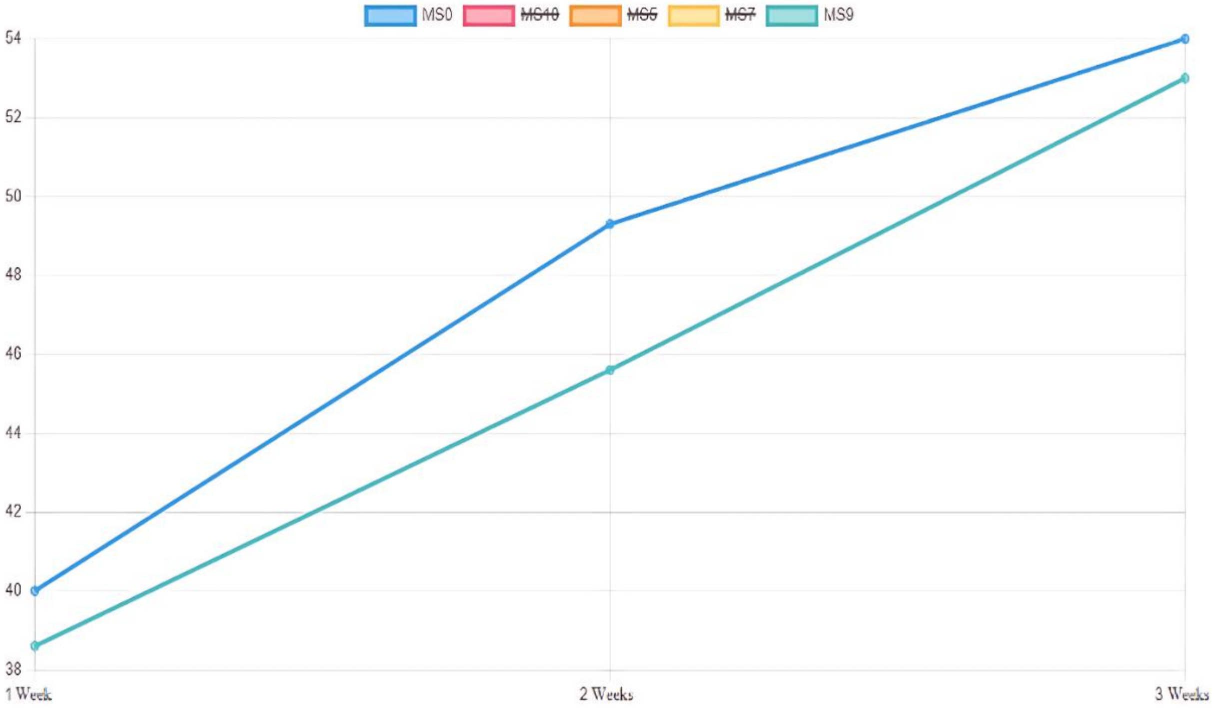

Figure 17.
Sampling by nutrient media.

When selecting the "Number of nodes" parameter, a visualization of nutrient media effectiveness is displayed, obtained based on the number of formed plant nodes (Figure 18).

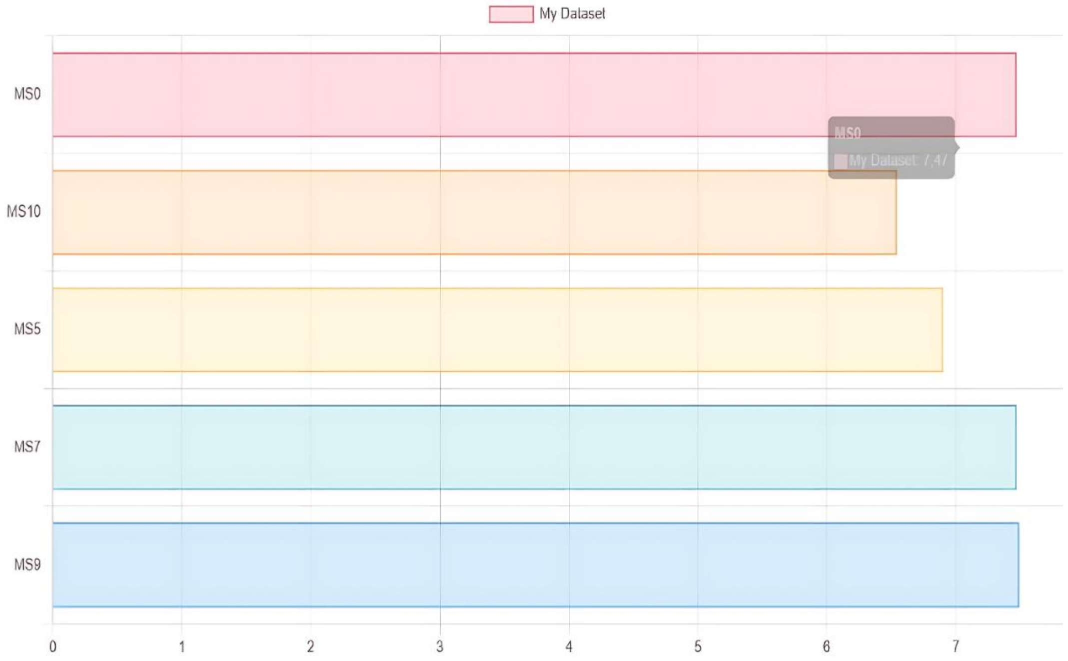

Figure 18.
Visualization of the effectiveness of nutrient media obtained depending on the number of plant nodes formed.

When selecting the "Root Formation Efficiency" parameter, a visualization of the nutrient media effectiveness is displayed depending on the root formation percentage (Figure 19).

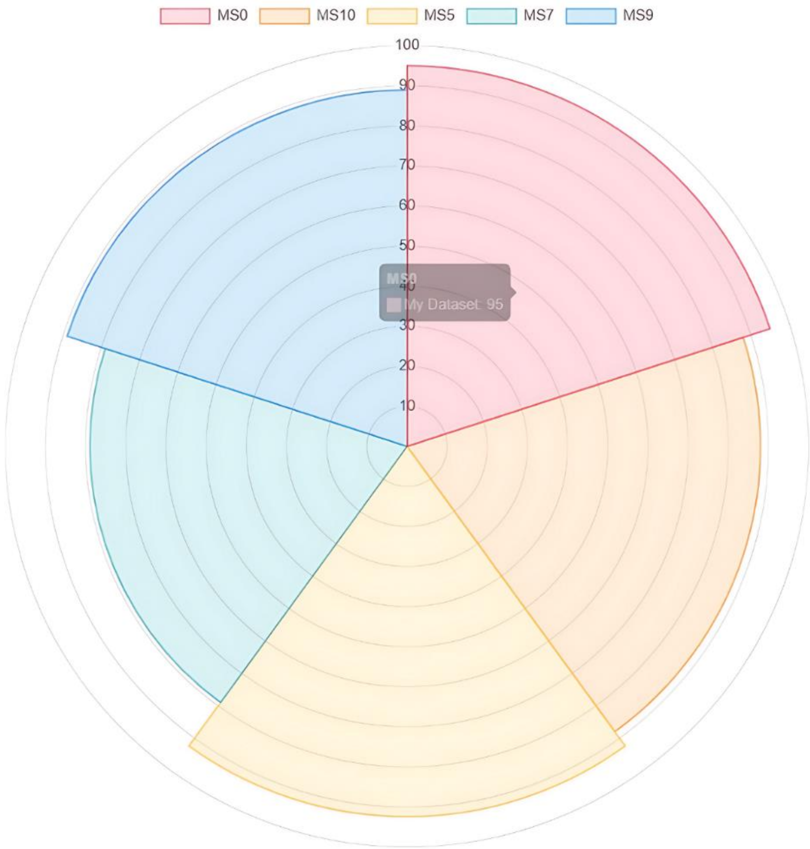

Figure 19.
Visualization of the nutrient media effectiveness depending on the root formation percentage.

The "Plant Development Analysis" tool compares the indicators entered by the user with the most effective ones (Figure 20). The user inputs the plant type, the concentration of phytohormones, and parameters of plant development such as plant height, number of nodes, and root formation efficiency. After the user adds the available data, a table and graph displaying the deviation of the user's indicators from the most effective indicators for the selected parameter are presented (Figures 21-22).

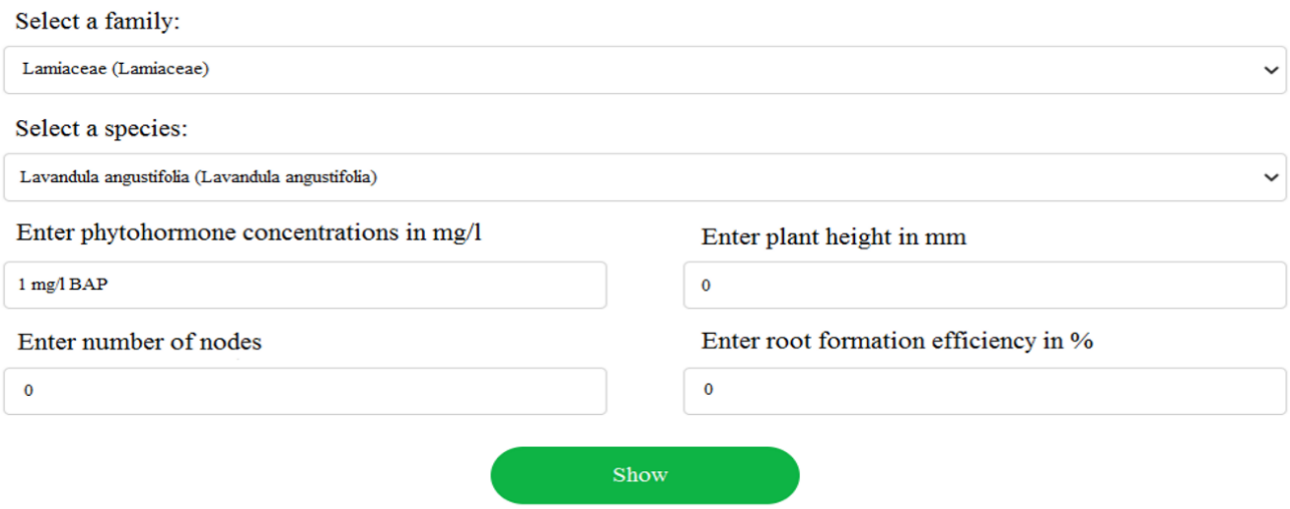

Figure 20.
Entering parameters in the "plant development analysis" tool.

The optimal selection of nutrient medium was made for the species Lavandula angustifolia (Lavandula angustifolia):

Name of medium	Composition of the medium	Plant height in mm	Rooting in %	Number of nodes in pcs
Recommended data	0.5 mg/l BAP + 2 mg/l IMC	72	90	10.55
User data	1 mg/l BAP	56	65	2

Figure 21.
Comparative table of recommended data and user data in the "plant development analysis" tool.

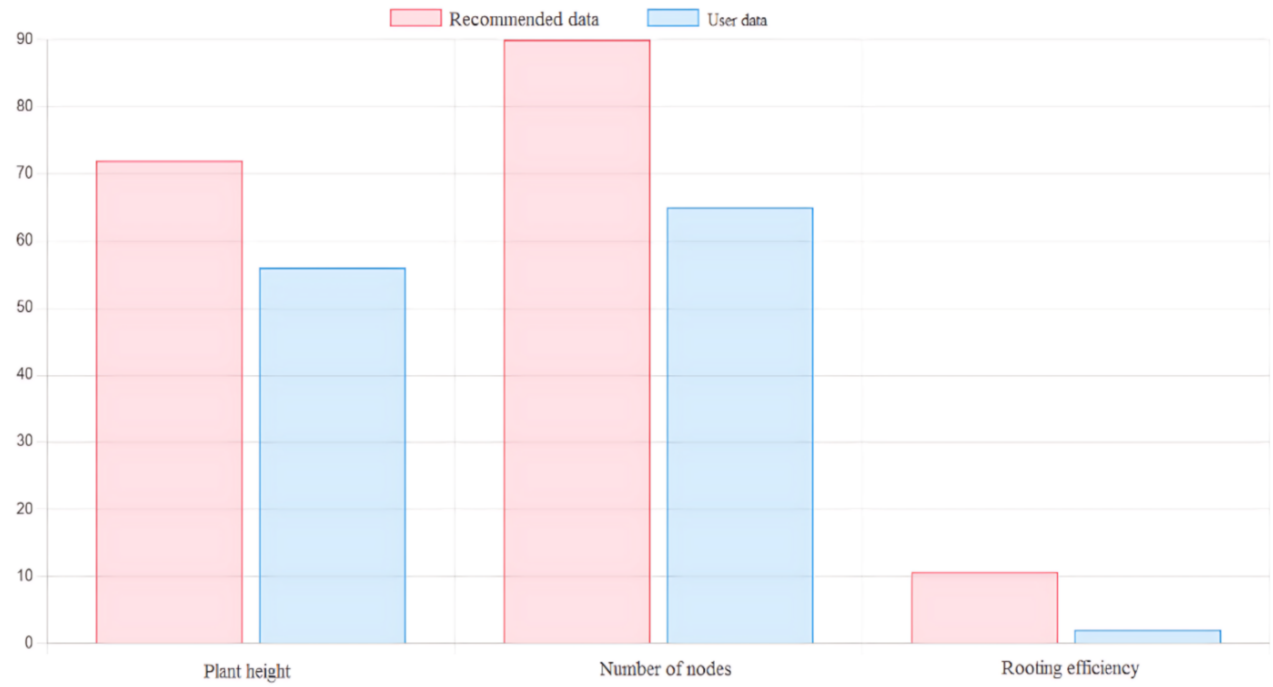

Figure 22.
Visualization of plant development analysis.

The clonal micro-propagation system also has a unique tool - "Intelligent analysis," which allows predicting the values of important indicators of cell culture based on data on key cultivation parameters. This module is integrated into the web application and is accessible to users through a user-friendly interface.

During the development of this analytical module, a series of experiments were conducted with various machine learning algorithms to determine the most appropriate model. Among the models considered are linear regression, Ridge regression, Lasso regression, random forest, and the support vector machine (SVR) model. Each of the models under consideration was trained on a training sample and then tested on a test sample. Metrics such as mean square error (MSE) and the coefficient of determination (R-squared) were used to assess forecasting quality. The comparison showed that the support vector machine (SVR) model demonstrated the best results in prediction accuracy, noise resistance, and learning speed. Other models showed lower performance or were less interpretable (Figure 23).

```
Linear Regression:
R-squared: 0.96
Mean Squared Error: 0.00
Ridge Regression:
R-squared: 0.96
Mean Squared Error: 0.00
Lasso Regression:
R-squared: -0.02
Mean Squared Error: 0.11
Random Forest Regressor:
R-squared: 0.93
Mean Squared Error: 0.01
Support Vector Regression:
R-squared: 0.97
Mean Squared Error: 0.00
```

Figure 23.
Evaluation of the quality of machine learning algorithms.

The support vector machine (SVR) model was used to implement the forecasting. It is a powerful machine learning algorithm that has proven itself well in regression tasks. The model was trained on a dataset that includes information about cultivation parameters, including the plant species, concentrations of various phytohormones, and the corresponding values of cell culture indicators.

After training, the SVR model was saved as a pkl file, which is downloaded when the web application is launched. When the user enters the values of the cultivation parameters into the web form, this data is converted into a format suitable for the model and transmitted to it for input. The SVR model performs forecasting and returns the expected values of cell culture indicators, which are displayed to the user. The forecast based on the SVR model is implemented on the "Plant Development Forecast" tool page, which displays background information on plant species and phytohormones.

In the forecast form, the user enters the plant species and the concentrations of phytohormones used, and then receives the predicted callus formation coefficient, which takes values from 0 to 2. This coefficient shows how effective this nutrient medium is for a particular plant species (Figure 24).

Figure 24.
Data entry and the results of the callus formation coefficient forecasting.

Thus, the introduction of an analytical module into the clonal micropropagation management system contributes to improving the efficiency and competitiveness of biotechnological industries by optimizing the processes of clonal micropropagation of plants.

4. Conclusion

The information system models described in the article by the author, focused on the process of managing clonal micro-propagation, are based on the principles of implementing expert systems. The developed intelligent system is based on the knowledge and experience of experts in the field of biotechnology. Additionally, in its implementation, the rules, logic, and knowledge base of the subject area under consideration were utilized. Information about the plant, the nutrient medium, and the parameters of plant development are used as input data. The implementation of algorithms for processing available source data on agricultural crops allows for solving the tasks of employees and managers of agricultural entities: calculating the optimal nutrient medium for the selected plant, visualizing plant development based on the entered data, and evaluating plant development according to the optimal and selected nutrient medium.

Thus, it can be noted that the intellectual management system of clonal micro-propagation proposed by the author will contribute to the development of the biotechnology industry as a globally competitive field of agriculture aimed at improving crops and increasing their productivity and resistance to adverse conditions.

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