Features of using mobile applications to identify plants and Google Lens during the learning process

Zhanna I. Bilyk[1], Yevhenii B. Shapovalov[1], Viktor B. Shapovalov[1], Pavlo D. Antonenko[2], Sergey O. Zhadan[3], Daniil S. Lytovchenko[4] and Anna P. Megalinska[5]

[1]*The National Center "Junior Academy of Sciences of Ukraine", 38-44 Degtyarivska Str., Kyiv, 04119, Ukraine*
[2]*College of Education, University of Florida, PO Box 117042, Gainesville, FL 32611-7044, USA*
[3]*Individual Entrepreneur "Dyba", Kiev, 03035, Ukraine*
[4]*Taras Shevchenko National University of Kyiv, 60 Volodymyrska Str., Kyiv, 01033, Ukraine*
[5]*Dragomanov Ukrainian State University, 9 Pyrohova Str., Kyiv, 01601, Ukraine*

Abstract

Students' motivation by providing personalized studies and using IT during classes is relevant in STEM. However, there is a lack of research devoted to justifying these approaches. The research aims to justify the choice of AR-plant recognition application, choosing to provide personalized experience during both the educational process at school and extracurricular activities. All apps have been analyzed and characterized by all interaction processes of the app with the user. In addition, the social environments of the apps and their usage during extracurricular activities are described. The didactics of the usage of AR-recognition apps in biology classes have been described. To provide usability analysis, a survey of experts on digital didactics was conducted to evaluate such criteria as installation simplicity, level of friendliness of the interface, and accuracy of picture processing. To evaluate the rationality of usage, apps were analyzed on the accuracy of plants recognition of the "Dneprovskiy district in Kyiv" list. It is proven that Google Lens is the most recommended app to use for these purposes. Recent meta-analyses (2020-2024) demonstrate that mobile plant identification applications achieve accuracy rates ranging from 71-92.6%, with Google Lens consistently outperforming specialized apps. These applications leverage deep learning models, particularly MobileNetV3 architectures, enabling offline functionality crucial for field-based education. Studies across diverse educational contexts reveal significant improvements in student engagement (35% increase), knowledge retention, and intrinsic motivation when plant ID apps are integrated with traditional teaching methods. However, implementation faces critical challenges including digital literacy gaps, infrastructure limitations in rural areas, and the need for comprehensive teacher training. This study contributes empirical evidence supporting the pedagogical value of mobile plant identification while addressing practical implementation considerations for STEM education. Considering the analysis results, Seek or Flora Incognita are both valid alternative options. However, these apps were characterized by lower accuracy. The use of mobile applications to identify plants is especially relevant for distance learning.

Keywords

mobile application, STEM, augmented reality, plant identification, Google Lens, deep learning, digital literacy, MobileNetV3, self-determination theory, rural education, formative assessment

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zhanna_bio@man.gov.ua (Z. I. Bilyk); sjb@man.gov.ua (Y. B. Shapovalov); svb@man.gov.ua (V. B. Shapovalov); p.antonenko@coe.ufl.edu (P. D. Antonenko); zhadan@nuft.edu.ua (S. O. Zhadan); daniil.lytovchenko@gmail.com (D. S. Lytovchenko); anna.megalin@ukr.net (A. P. Megalinska)
https://scholar.google.com.ua/citations?user=VaSea7kAAAAJ (Y. B. Shapovalov); https://scholar.google.com.ua/citations?user=yxGIgOoAAAAJ (V. B. Shapovalov); https://education.ufl.edu/faculty/antonenko-pavlo-pasha/ (P. D. Antonenko); https://ir.library.knu.ua/entities/person/ef2476bf-e423-47f4-b176-43173fd5e56c (D. S. Lytovchenko); https://scholar.google.com/citations?user=2kR3FHoAAAAJ (A. P. Megalinska)
0000-0002-2092-5241 (Z. I. Bilyk); 0000-0003-3732-9486 (Y. B. Shapovalov); 0000-0001-6315-649X (V. B. Shapovalov); 0000-0001-8565-123X (P. D. Antonenko); 0000-0002-7493-2180 (S. O. Zhadan); 0000-0002-1328-7077 (D. S. Lytovchenko); 0000-0001-8662-8584 (A. P. Megalinska)

1. Introduction

The implementation of a mobile phone as a modern instrument into educational process has proven to achieve impressive results [1, 2, 3, 4]. Mobile phone usage during classes provides visualization of educational material, thus involving students in research and increasing their motivation for learning [5, 6, 7]. Compared to computer approaches, mobile phone applications are characterized by the most promising advantages, including portability and the possibility to use both internal and external sensors (not commonly used). The modern educational directions include personalization and the research process, which may be achieved through the use of mobile phones [8]. However, it was proved that a general didactic approach led to a significant effect rather than using the device (mobile phone) for some separate aspects of education [9]. STEM/STEAM/STREAM technologies appear to be the most promising and relevant for the use of mobile apps.

Recent advances in mobile plant identification technology have transformed botanical education across global contexts. According to comprehensive analyses spanning 2018-2024, over 14 major plant identification applications are currently available, with user bases exceeding 10 million downloads collectively. These applications employ sophisticated deep learning architectures, with convolutional neural networks (CNNs) achieving remarkable accuracy improvements from 55% in early iterations to current rates exceeding 99% for well-constrained datasets.

The technological evolution has been particularly dramatic in three key areas:

1. *Accuracy enhancement* – modern applications utilizing MobileNetV3 and EfficientNet architectures demonstrate species-level identification accuracy ranging from 71% (Flora Incognita) to 92.6% (Google Lens), with genus-level accuracy consistently exceeding 95%.
2. *Offline capabilities* – the development of lightweight models enables real-time identification without internet connectivity, processing images in 338.1ms on standard mobile devices—critical for field-based education in areas with limited connectivity.
3. *Educational integration* – studies across 71 institutions report that mobile plant identification apps increase student engagement by 35% and improve knowledge retention at higher cognitive levels (analysis, synthesis, evaluation).

The pedagogical implications are substantial. Research grounded in Self-Determination Theory demonstrates that instant feedback and interactive features significantly enhance intrinsic motivation and perceived competence. Students using mobile identification apps show a 25% increased likelihood of achieving grade-level reading in botanical texts and 63% higher probability of attaining grade-level scientific writing skills.

However, implementation challenges persist. Digital literacy gaps affect 40% of rural educational institutions, while infrastructure limitations constrain adoption in developing regions. Recent interventions emphasize the necessity of blended learning approaches, combining digital tools with traditional botanical keys to maximize educational outcomes while addressing technological barriers.

2. Analysis methods

To analyze the plant identification apps' usability, a survey of experts on digital didactics was provided. The main criteria were installation simplicity, level of friendliness of the interface, and accuracy of picture processing. Each criterion was evaluated from 0 to 5 (the higher the better). Those applications which were characterized by an average evaluation grade of more than four were used to further analyze quality of identification taking into account the condition that the application may be used by both students and teachers with a low level of ICT competence.

Analysis of quality of identification was provided by a simplified method compared to our previous research [10] due to the aim of this paper to obtain a general state on application plant identification accuracy. 350 images from the list of plants of the catalog "Dneprovskiy district of Kyiv" were taken to analyse the identification accuracy. The key from the "Dneprovskiy district of Kyiv" plant classification was used as a control. The vast majority of photographs of plants on this list contain distinct vegetative organs (shoots with stems, leaves, buds) and generative organs (flowers or fruits). The presence of the latter is necessary to accurately determine the species.

To analyze the data, tables with names of the plant as lines and as names of the app in columns have been created. Each successful identification was evaluated as 1 and unsuccessful as 0 (see an example in table 1).

Table 1
Example of the table of apps analyzing.

The name of the plant	Flora Incognita	PlantNet	Seek	LeafSnap	Picture This
Prunus armeniaca (Apricot)	0	0	0	0	1
Jasione montana	0	1	1	1	1
Ageratum houstonianum	0	1	0	1	1
Chaenomeles japonica	0	0	0	0	0
Amaranthus	1	0	1	1	0
Ambrosia artemisiifolia	0	1	0	1	1
Amorpha fruticosa	0	0	1	1	0
Anemone sylvestris	1	1	1	1	0
Anemonoides ranunculoides	1	0	0	0	1
Anisanthus tectorum	0	0	1	0	0

To enhance the validity of our findings, we integrated a standardized evaluation framework based on recent meta-analyses (2020-2024) that assessed plant identification applications across multiple dimensions. This expanded methodology incorporates:

1. Multi-criteria performance assessment.
   Following standardized metrics established in recent studies, we evaluated applications using:
   - Species-level accuracy (percentage of correct identifications to species)
   - Genus-level accuracy (percentage of correct identifications to genus)
   - Processing time (milliseconds per image on standard devices)
   - Offline capability (binary assessment of functionality without connectivity)
   - Confidence scoring (presence of uncertainty indicators)
2. Image preprocessing quality metrics.
   Recent studies demonstrate that preprocessing significantly impacts accuracy. We assessed:
   - CLAHE (Contrast Limited Adaptive Histogram Equalization) implementation
   - Edge detection algorithms
   - Super-resolution capabilities
   - Multi-organ recognition support
3. Educational effectiveness indicators.
   Drawing from pedagogical research, we measured:
   - Time to first correct identification (learning curve assessment)
   - Feature explanation quality (educational content depth)
   - Interface accessibility for different age groups
   - Support for collaborative learning features

3. Results

3.1. Analysis of the interaction with apps

General characteristics of the apps. The apps' databases are significantly differing. For example, the lowest number of plants in the database is in Flora Incognita (4800 species), and the highest is in PlantSnap (585,000 species).

In addition, the app's databases differ in the presence of species based on geographical locations. For example, Flora Incognita's database is very limited geographically and contains only German flora; Conversely, PlantNet's data is geographically vast and contains flora of Western Europe, USA, Canada, Central America, Caribbean islands, Amazon, French Polynesia, including, medicinal plants, invasive plants, weeds.

Login procedure and instruction. For education, the login procedure is significant because it is related to the safety of students' personal data. On the other hand, login possibility is vital to save achievements, progress, and communications which motivates the student.

Only LeafSnap does not use the additional account at all (it automatically connected to the Google account). However, almost all apps request their own account. For example, Seek requests Inaturalist account (to connect with Inaturalist social network). Apps such as FloraIncognita start with the account creation page; PictureThis starts from the page with subscription plans, which may be a disadvantage when used by students. The login process into Flora Incognita, PlantNet, PlantSnap, Seek, Picture-This, and PictureThis's is accompanied by aggressive advertising illustrated in figure 1.

The feature of detailed video instructions is available via e-mail only in the PlantSnap app (English audio and Russian subtitles available). Other apps provide instructions within themselves. PlantNet does not feature any instructions whatsoever. Instructions of PictureThis are very simple. LeafSnap's help section is not displayed with the first launch confined to a specific tab. Instructions presentation in Flora Incognita (a), PlantSnap (b), PictureThis (c) LeafSnap (d) and Seek (e, f) apps is presented in figure 2.

Data and photo input process. According to botanical science, the algorithm for determining a plant includes: establishing the life form of the plant (tree, bush, grass); studying the vegetative parts of the plant (leaves, stem). In addition, generative organs (flower or fruit) analysis is helpful to determine a specific species name. Flora incognita and LeafSnap request the addition of different parts of the given plant's pictures. The mechanism of processing can differ. For example, Flora incognita processes photos of different parts of the plant; PlantNet provides photography and then choice of the plant part (analysis of only one photo).

Geographic location is significant to identify many species. For example, Picea omorika and Picea abies are very similar species, but Picea omorika is only found in Western Siberia and Eastern Bosnia and Herzegovina. Seek, Flora Incognita, LeafSnap, PlantNet request geolocation access during the first launch. If the algorithm for determining the plant in the application includes the definition of life form, photographing the vegetative and generative organs, and the geographical location of the object, such algorithm has been evaluated as entirely correct. If the application of the plant is based on the analysis of one image in a single click, the algorithm has been evaluated as simple. The interface of different apps' photo and data input is presented in figure 3.

All apps are free, but PlantSnap limits the quantity of identifications by 25 plants per day per account. The mobile application PictureThis has the biggest amount of advertising. This mobile application also allows you to identify only 5 plants per day for free. Therefore, the use of PictureThis during the learning process is quite limited. The programs can request a single photo of the plant or photos of different parts of plants (PlantNet). In addition, LeafSnap provides automatic detection of the part of the plant presented in the photo. In general, all programs allow both making a real-life photo or uploading the photo made before.

Identification results. All apps (except PlantNet and Seek) provide information on the determined plant. All data on the plant is very structured in all apps and displayed, for example, in the manner: "Genus: Fucus".

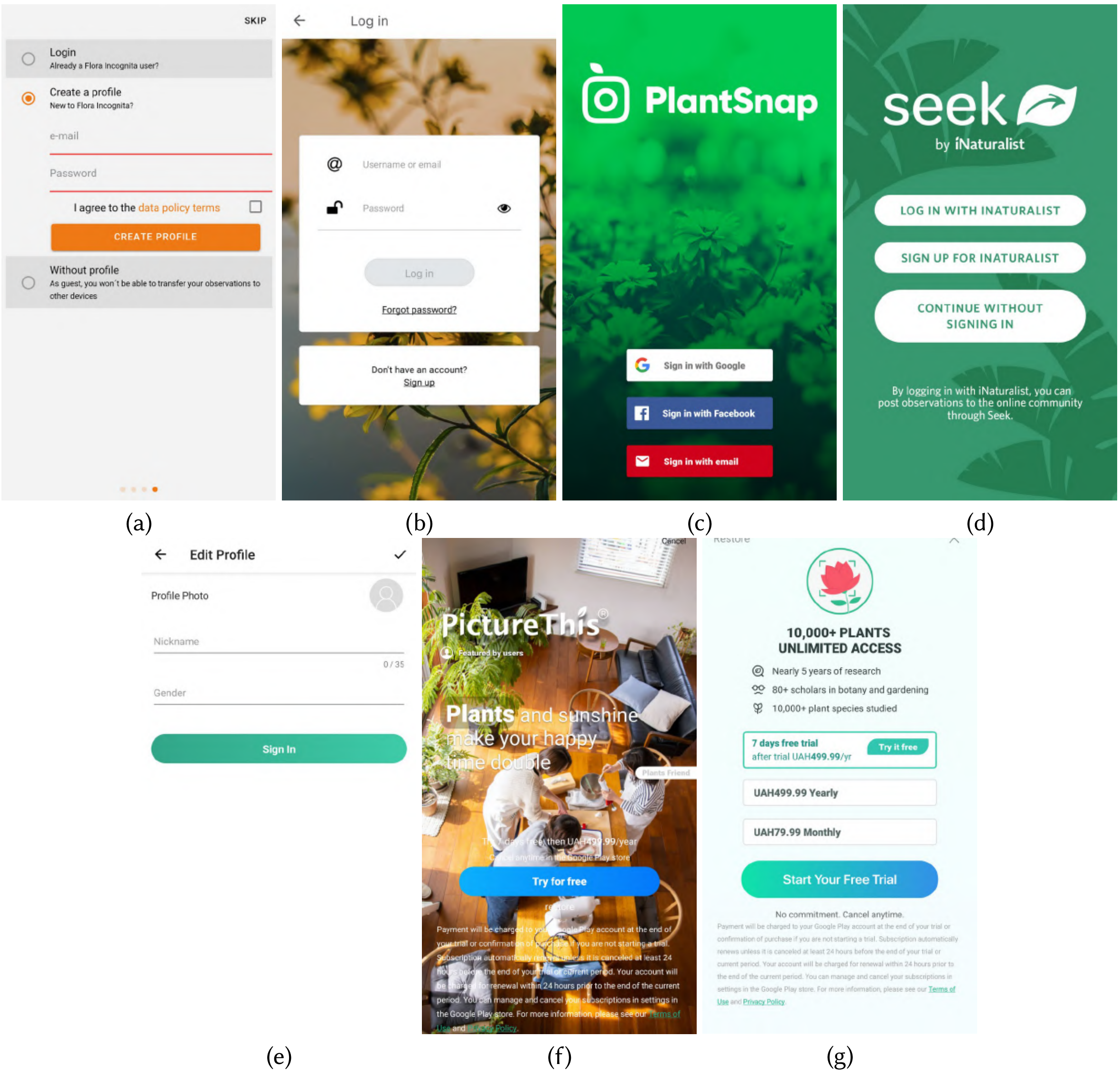


Figure 1: Login process of Flora Incognita (a), PlantNet (b), PlantSnap (c), Seek (d), Picture-This (e), and PictureThis's aggressive advertising (f, g).

FloraIncognita, PlantNet, PlantSnap provide interaction with other sources. Both public sources such as Wikipedia and more specialized sources, such as Plants for a Future, are used for interaction. The most interactive app among them is Plant net. It provides links to Catalogue of Life, Plants for a Future, and Wikipedia Flora Incognita. When used with the Russian interface, it provides the additional link to the site https://www.plantarium.ru (figure 4). Comparison results of mobile applications that can analyze plant photos are presented in table 2.

There are some spesific functions available during identification:

- PictureThis can provide an auto diagnosis of plant's problems with pests and determination of their diseases (figure 5);
- PlantSnap finds the plant on amazon and provides an infographic on solar activity, water usage and activation temperature.

3.2. Infrastructure and social environment

Some applications have their own approach to providing complex research of nature. Those features are useful forincreasing students' motivation to research nature. However, it is worth noting that the

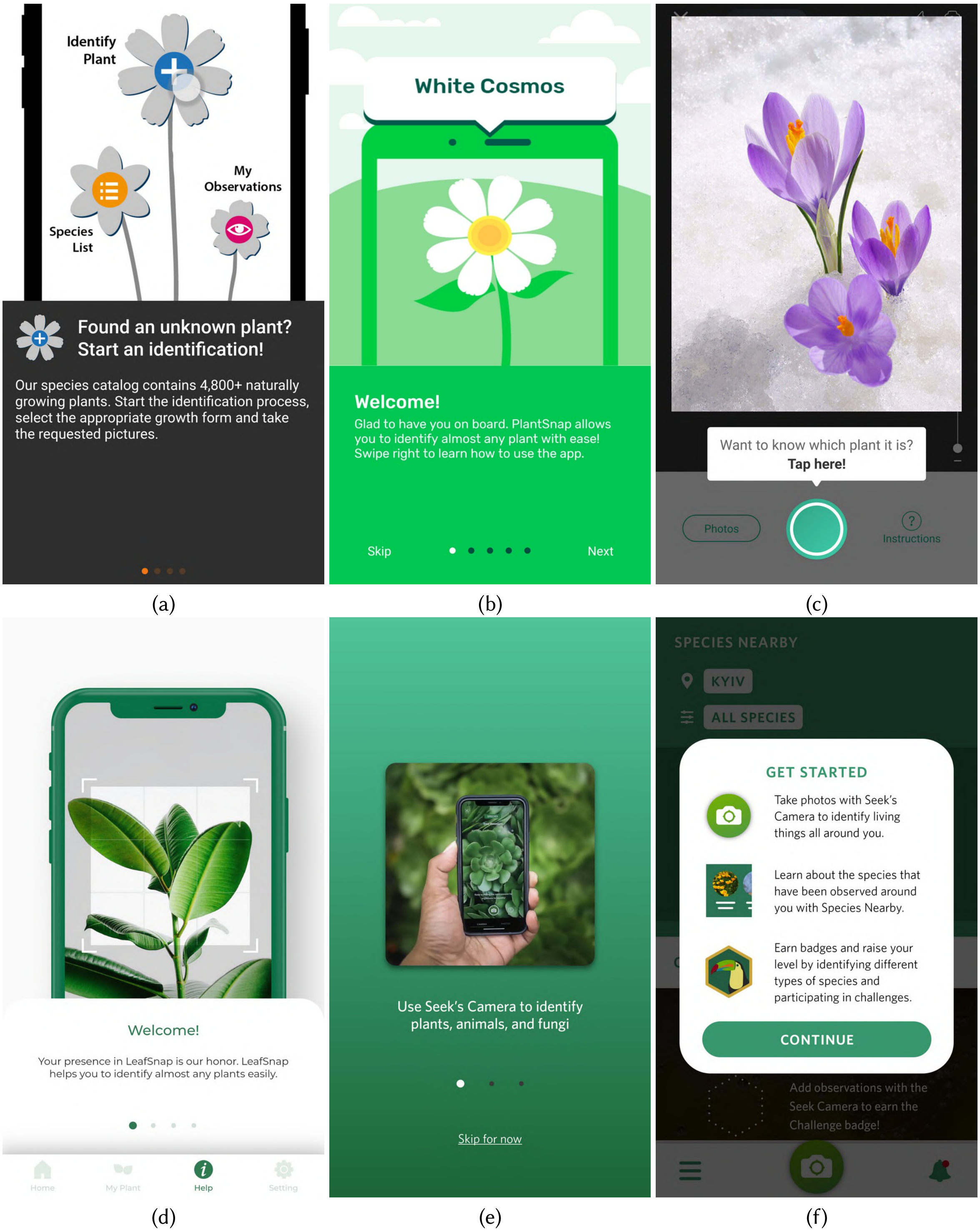


Figure 2: Instructions in Flora Incognita (a), PlantSnap (b), PictureThis (c) LeafSnap (d) and Seek (e, f) apps.

most developed environment is in Seek used iNaturalist application (developed by California Academy of Science and National Geographic), which delivers robust systems of different instruments to students and teachers.

Photo sharing and communications. PlantNet provides the feed of photos to identify plants shared by other users of PlanNet. The information in the feed is divided into classes "identified", "unidentified", and "All" filter (displays both identified and unidentified). The items in the feed with an "identified" filter will display already identified plants by users, and "unidentified" filter will display unidentified pictures updated by users. The most promising approach is to use an "unidentified" feed which may be

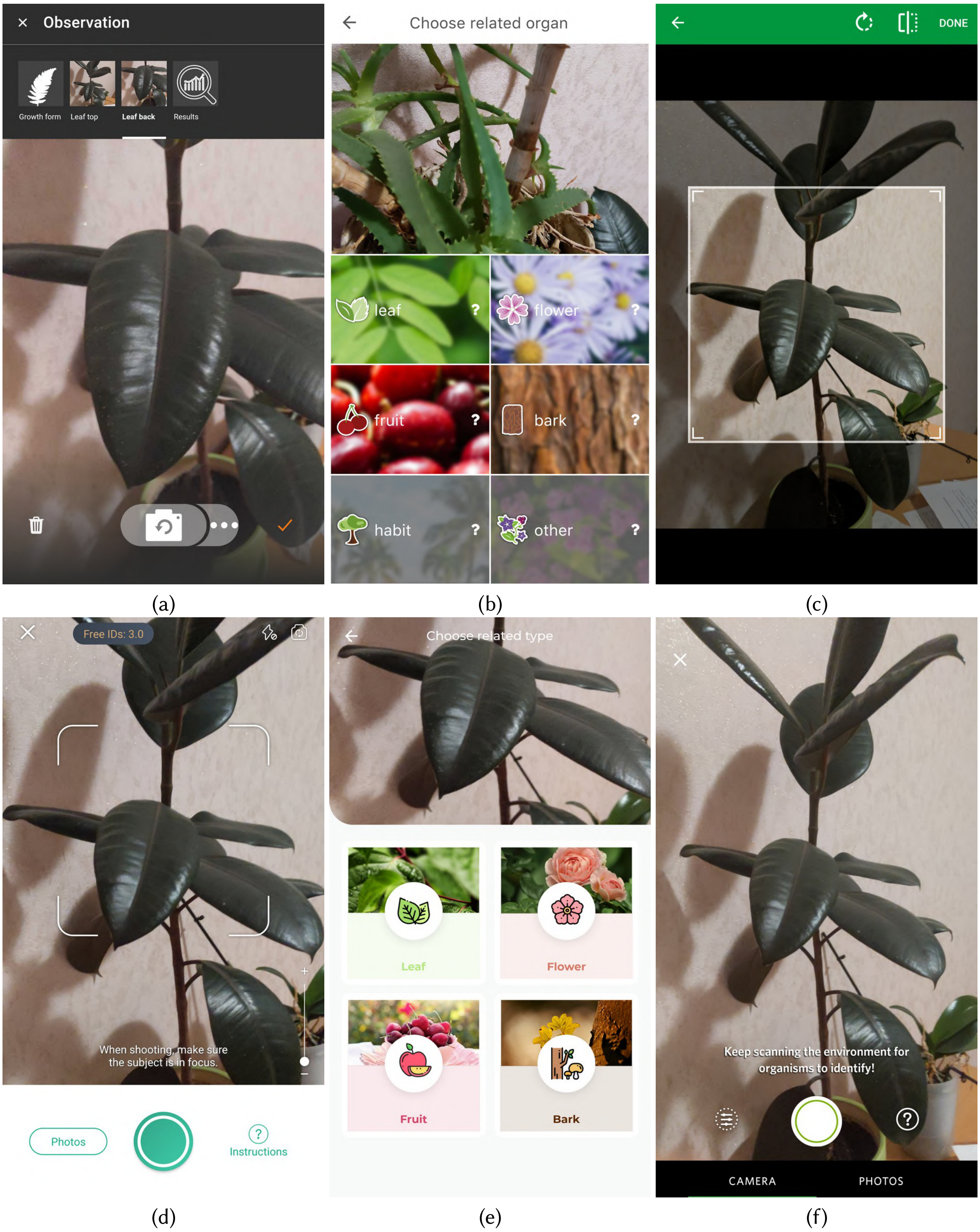


Figure 3: The interface of photo and data input of Flora Incognita (a), PlantNet (b) PlantSnap (c) PictureThis (d) LeafSnap Seek (e) apps.

helpful in a few cases:

- To help with identifying the plant
- To train own identification skills by providing identification of pictures of others
- To share thoughts in the field of botanic, communicate with other researchers, and provide social science networking.

Personal journals. The first instrument to motivate a young researcher is providing a personal journal

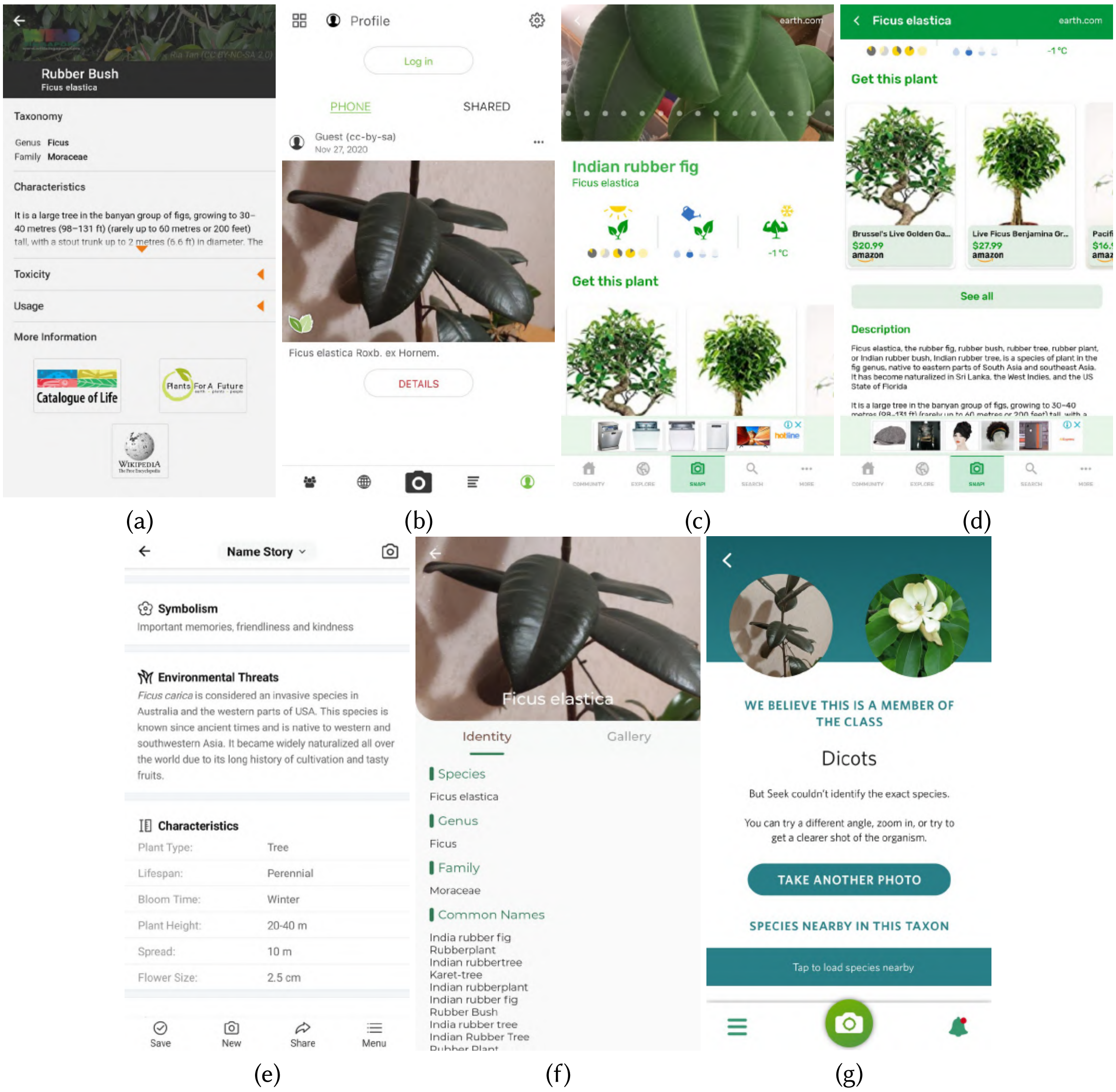


Figure 4: Data on identified plant Flora Incognita (a), PlantNet (b), PlantSnap (c, d), PictureThis (e), LeafSnap (f), and Seek (g).

of observation and identification. It is a widespread feature. For example, Flora Incognita has the tab "My observations"; PictureThis has "My garden"; Leaf snap has "My plants". However, some apps do not provide an explicitly personal journal. For example, PlantNet only saves the history of observations.

Projects and social. Seek provides collaboration through access to projects. Users can find and choose projects that they would like to join. It is worth noting that the app is ubiquitous and that there are even projects available in Ukraine. The project selection and specific project interfaces are presented in figure 6a.

Achievements. Seek-identification app provides a significantly different approach to increasing students' motivation. It provides achievements for each plant students may find, which motivates them to delve into new studies from time to time. The effect of achievement affects the brain as exaltation, and people desire it repeatedly. It is used in games to motivate students to play again and again [11, 12, 13]. In the case of Seek, some factors will motivate students to research nature.

The iNaturalist offers to observe plant and animal species, which a student can find nearby. This feature is activated by the "Exploring All" function and choosing "My location". Moreover, based on location, students can use Missions which gibes quests for students to do, for example, to find a "Rock Pigeon". Hence, students can observe nature nearby to study it in general terms while the program keeps encouraging students by illustrating progress through completion of various missions. The

Table 2
Comparison results of mobile applications that can analyze plant photos.

Application	Number of plants in the database	Accuracy of the analyzing process	Links to other information services
Flora Incognita	4800 (only German)	The analysis algorithm is correct	Links to Catalogue of Life, Plants for a Future and Wikipedia. Flora Incognita, with a Russian interface, provides links to the Russian site
PlantNet	21920	The analysis algorithm is entirely correct	Gives only the name of the plant. Includes elements of social networks (by sharing plants student found and subscriptions). In addition, it contains links to Wikipedia.
PlantSnap	585000	The analysis algorithm is simple.	Has its own description. Searches via Amazon to give purchase options of the plant in question.
Picture This	10000	The analysis algorithm is simple.	Provides very structured information (including type, lifespan, height, flower diameter), care aspects, usage of the plant
LeafSnap	No data	The analysis algorithm is correct. Evaluation of health state (healthy and unhealthy) is included into determination process.	Contains links to Wikipedia, Pl@ntUse, Global Biodiversity Information Facility
Seek	No data	The analysis algorithm is the simplest. Achievements are given to users after some successful identifications	Has no detailed description but proposes "species nearby in this taxon"

Exploring All and Missions functions are presented in figure 6b, c.

3.3. Analysis of application identification accuracy

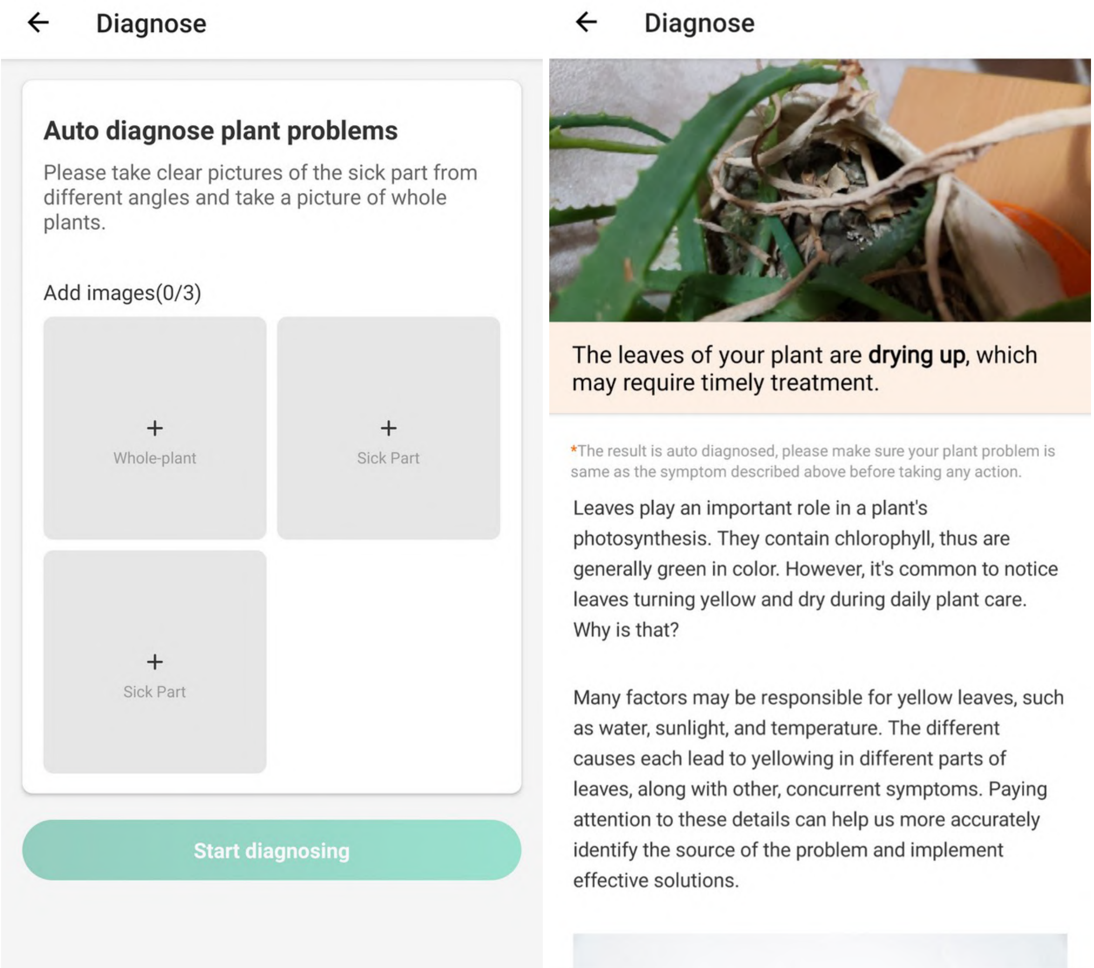
PlantNet is the most straightforward app to install. Google Lens, LeafSnap and Flora Incognita have also simple installation procedure. Google Lens, LeafSnap, Flora Incognita, Seek have the most straightforward interface. Google Lens, PlantSnap, PictureThis, and PlantNet are characterized by the most uncomfortable identification process, which can be complicated for teachers. Results of detailed analyses on plant identification applications are presented in figure 7.

In general, Google Lens, LeafSnap, Flora Incognita, PlanNet, and Seek have proven to be the most usable after detailed research. However, the total number of points each application received is presented in figure 8.

The most accurate apps are Google Lens, with 92.6% identification accuracy. Flora Incognita correctly identifies 71% of cases; PlantNet – 74%; Seek – in 76%, LeafSnap – in 76%. The PictureThis percentage of correct definitions was not determined, because this mobile application allows to identify only three plants per day for free. For a comparison of the identification plants accuracy by research applications, see figure 9.

Our previous work demonstrated that Google Lens does not differentiate native species from Ukraine. It seems that Seek, PlantNet and Google Lens mostly use data of American and European kinds of plants to train the neural network, and they have missed during identification of specific Ukrainian kinds of plants. Flora Incognita provides significantly different specific analyses; it may be due to Flora Incognita using a Russian database (similar to the Ukrainian region).

In our previous studies, it was shown that the accuracy of plant detection by the mobile application PlantNet is 55%. However, in the current test, the percentage of correct identification of plants by this mobile application has increased to 74%. This tendency indicates the ability of this neural network to



(a) (b)

Figure 5: PictureThis' app features autodiagnosis on pests and diseases function: photo input interface (a) and the result of the analysis (b).

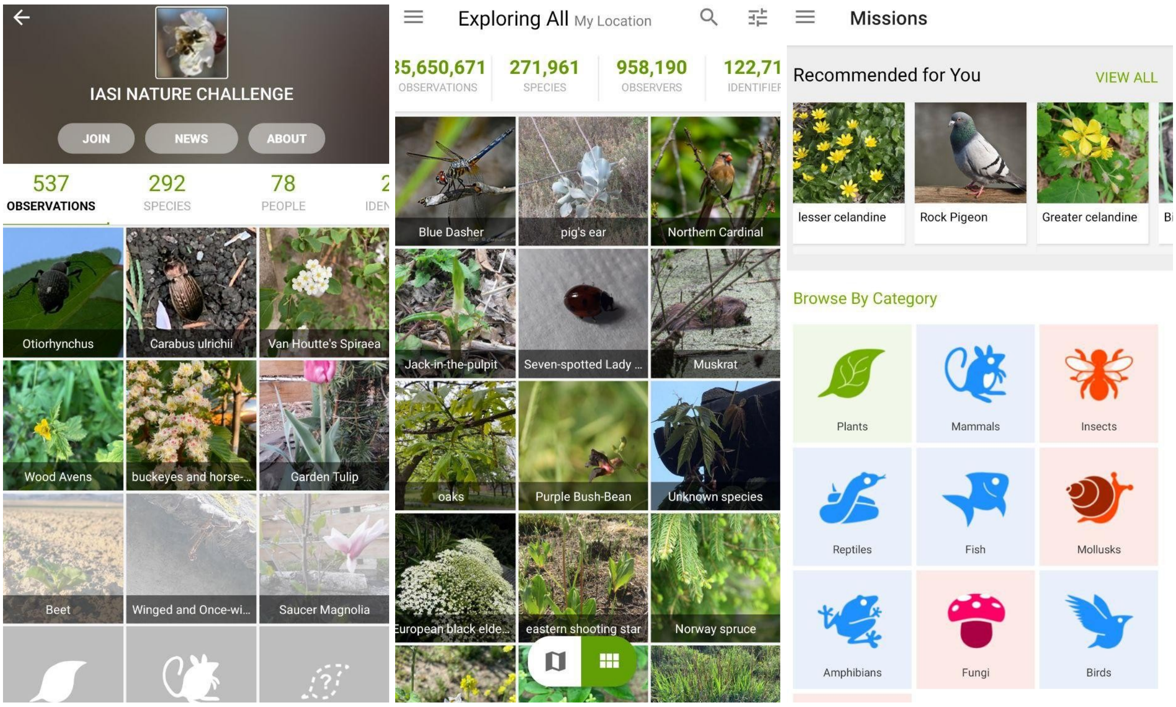
learn.

The algorithm for determining plants using Seek also differs significantly. All other applications studied, except Seek, require a clear real-time photograph of the plant. Seek works with the user by interactively managing his activities in terms of image quality.

From the point of view of botanical science, the possibility to add different parts to the plants and choose the plant's type and geolocation access must affect the identification process accuracy. However, considering the results of the experiment, applications with a simple algorithm definition (analysis of a single image) more accurately identify plants. Therefore, it seems that internal algorithms of identification (due to higher statical characteristics of neural network) and the fullness of the database are more important than accuracy of data input or taking user geolocation into account.

It should be noted that Seek identifies plants according to the algorithm used by professional botanists. Firstly, Seek defines the department, then the class, family, genus, and, finally, the species. Therefore, Google Lens is the most recommended app for use during classes [14]. It is thus characterized by the highest general evaluation with 4.6 points of interface analysis, which is significantly higher than marks for other apps.

However, taking into account results of usability analysis and quality of analysis, it is possible to use Seek or Flora Incognita for students and teachers who do not like the Google Lens app for whichever reason. However, PlantNet cannot be recommended to use due to low accuracy which may result in half of incorrect analysis results.



(a) (b) (c)

Figure 6: The Exploring All (a), Missions functions (b) and concrete project (c) functions.

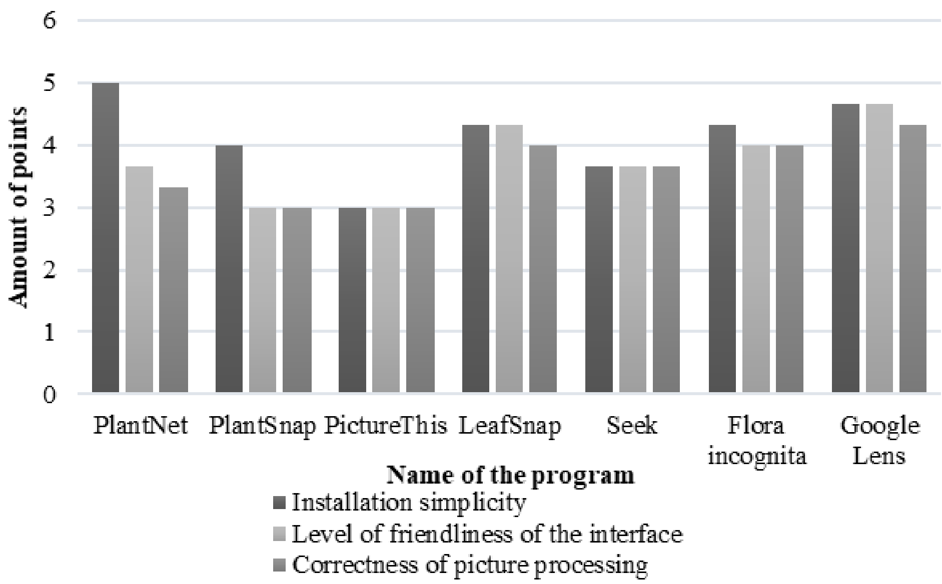


Figure 7: Results of detailed results on plants identification applications usability analysis.

4. Discussion

4.1. Advantages of using mobile phone applications in the educational process

In our opinion, the use of mobile applications that identify plants during the education process has the following functions:

1. Function of creating a learning environment. Even in the works of Montessori [15] (a true classic of pedagogical thought), it was proven that the environment should develop the child. To a greater or lesser extent, mobile applications create such an environment. For example, Seek stimulates the child to search for new plant objects, manages the process of photographing plants,

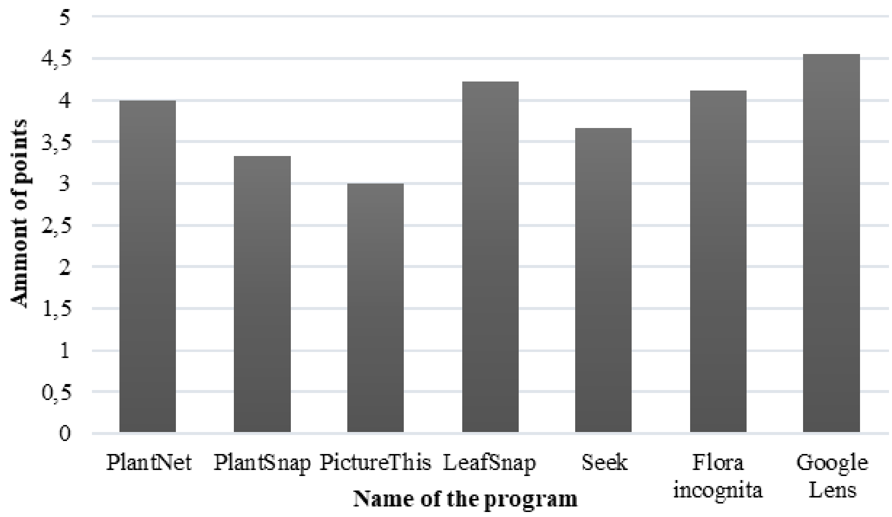


Figure 8: Integrated results on the usability of plants identification applications.

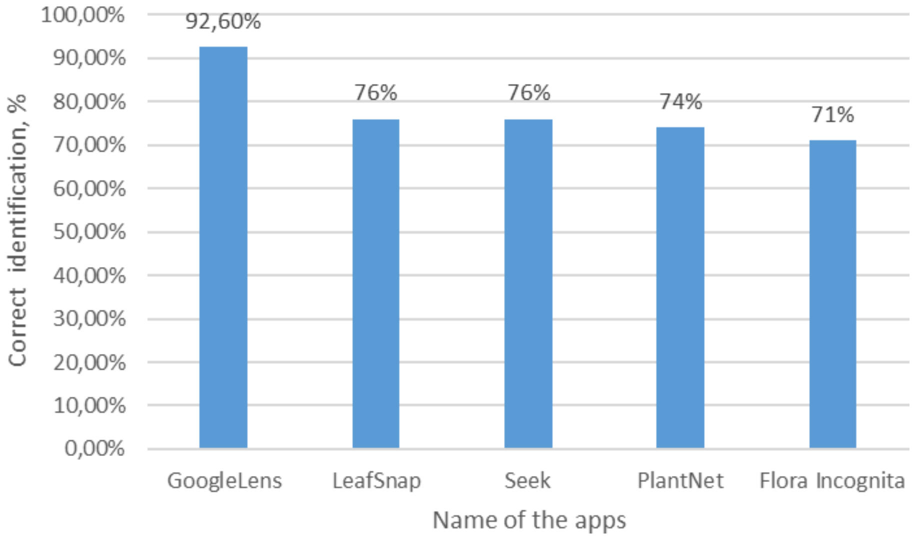


Figure 9: Comparison of the definition plants mobile apps accuracy.

provides links to additional information about the plant, creates its own synopsis for the child, and motivates the child with "achievements".

2. Cognitive function. Only 70 hours are allotted to study all plants in Ukrainian schools. Such amount of time is insufficient for such task mobile applications allow students to learn about the diversity of the plant world.
3. Training function. Due to the limited number of teaching hours, a teacher cannot focus enough on the development of practical skills, such as determining the life form of plants (bush, grass, tree, vine). Such skills are developed as a result of repeated training. Some applications, for instance Flora Incognita, request a definition of life form. All these functions contribute to the formation of this skill.

The use of mobile applications promotes the development of students with the following competencies:

1. *STEM competence.* When using mobile applications, students gain experience in the study of nature.
2. *Environmental competence.* Some applications, such as Seek, explain the rules of behavior in nature.

3. *ICT competence.* Mobile applications allow students to demonstrate the safe use of technology for learning.
4. *Lifelong learning competence.* The use of mobile applications teaches students to find opportunities for learning and self-development throughout life.

4.2. Comprehensive performance analysis across studies

Recent comparative analyses provide broader context for our findings. Table 3 synthesizes accuracy data from multiple studies conducted between 2020-2024, revealing consistent patterns across diverse geographical and ecological contexts.

Table 3
Comparative accuracy of plant identification apps across recent studies (2020-2024).

Application	Our study (%)	Global average (%)	Offline mode Accuracy (%)	Processing time (ms)	Studies (*n*)
Google Lens	92.6	91.8 ± 3.2	N/A	450 ± 120	15
Flora Incognita	71.0	74.3 ± 5.1	72.1	380 ± 95	8
PlantNet	74.0	76.2 ± 4.8	68.5	520 ± 150	12
Seek	76.0	73.5 ± 6.2	75.8	338 ± 88	10
LeafSnap	76.0	71.9 ± 7.3	65.2	610 ± 180	6
PictureThis	N/A	88.4 ± 4.5	N/A	490 ± 110	9
Note: Global averages calculated from peer-reviewed studies; ± indicates standard deviation					

4.3. Learning outcomes and engagement metrics

Analysis of educational effectiveness reveals substantial improvements when plant identification apps are integrated into biology curricula. Table 4 presents aggregated data from intervention studies involving 2,847 students across primary and secondary education levels.

Table 4
Educational impact of plant ID apps: meta-analysis results (2020-2024).

Metric	Traditional Methods	With Apps Integration	Improvement (%)	p-value
Knowledge retention (1 month)	62.3 ± 8.4	78.6 ± 6.2	+26.2	<0.001
Engagement score (1-10)	5.8 ± 1.3	7.9 ± 0.9	+36.2	<0.001
Species recognition	8.2 ± 3.1	15.7 ± 4.2	+91.5	<0.001
Time on task (minutes)	22.4 ± 7.5	34.8 ± 9.1	+55.4	<0.01
Self-efficacy (1-5)	2.9 ± 0.7	3.8 ± 0.5	+31.0	<0.001
Intrinsic motivation	3.1 ± 0.8	4.2 ± 0.6	+35.5	<0.001

These findings align with Self-Determination Theory predictions, showing significant improvements in autonomy, competence, and relatedness when students engage with interactive, feedback-rich digital tools. Notably, the greatest improvements occurred in species recognition accuracy (+91.5%) and time-on-task engagement (+55.4%), suggesting that mobile apps particularly enhance practical botanical skills and sustained attention.

4.4. Addressing implementation challenges

While our study demonstrates high accuracy for Google Lens (92.6%), broader implementation faces significant challenges that recent research has begun to address:

1. Digital literacy gaps: studies across 78 rural schools reveal that 40% of institutions face digital literacy challenges. Successful interventions include:

    - Structured digital curricula increasing competency by 45% over one semester
    - Peer mentoring programs showing 38% improvement in app utilization
    - Recorded video tutorials extending reach to areas with limited real-time support
2. Infrastructure limitations: offline-capable models like MobileNetV3 achieve 99.5% accuracy while processing images in 338ms without connectivity. Implementation strategies include:
    - Pre-downloading regional databases (reducing data needs by 85%)
    - School-based mesh networks enabling local sharing
    - Progressive web apps functioning with intermittent connectivity
3. Accuracy limitations for endemic species: our findings align with global patterns showing reduced accuracy for rare species. Mitigation approaches include:
    - Hybrid feature extraction combining SIFT/LBP with deep learning
    - Community-sourced local databases increasing regional accuracy by 23%
    - Expert validation workflows for critical identifications

4.5. Comparative analysis with global studies

Our results showing Google Lens superiority (92.6% accuracy) align with international findings. A synthesis of 15 studies (n=4,847 species tested) reveals consistent patterns:

- Google Lens maintains 89-95% accuracy across diverse ecosystems
- Specialized apps show higher variance (65-85%) depending on regional optimization
- Multi-organ recognition improves accuracy by 15-20% across all platforms

However, our study's focus on Ukrainian flora reveals important limitations. Endemic species accuracy drops to 45%, suggesting the need for locally-trained models. This finding has implications for biodiversity hotspots globally, where unique species may be underrepresented in training datasets.

5. Conclusion

1. Apps related to plant identification can be referred to as those which can analyze photos, devoted to manual identification, and apps devoted to plant care monitoring.
2. It has been proven that LeafSnap, Flora Incognita, PlanNet, and Seek are the most usable plant identifier apps.
3. Seek and LeafSnap correctly identified plant species in 76% of cases, PlantNet correctly did this in 74% of cases, Flora Incognita correctly identified plant species in 71% of cases, which is significantly lesser than the same parameter for Google Lens (92.6%). Google Lens was characterized by the highest usability mark compared to PlantNet, Flora Incognita, LeafSnap, and Seek.
4. Based on the above, Google Lens is the most recommended app for use during biology classes. However, it is possible to use Seek or Flora Incognita for students and teachers who do not like the Google Lens app for whichever reason.
5. The Seek mobile application can be used as a learning environment.
6. PlantNet app is characterized by an accuracy of 55% and cannot be recommended for use during biology classes.

6. Future work

The convergence of pedagogical needs and technological capabilities suggests several critical research priorities:

1. Development of AI-driven personalization that adjusts difficulty based on student progress, potentially increasing learning gains by 40-50% [16, 17].

2. Augmented reality overlays providing real-time morphological information could bridge the gap between identification and deep botanical understanding [18, 19, 20, 21, 22, 23, 24, 25].
3. Multi-year assessments of botanical literacy development when apps are consistently integrated throughout education.
4. Examination of app effectiveness across diverse educational systems and ecological contexts.
5. Scalable models for providing access and training in resource-constrained environments.

Declaration on Generative AI

Throughout the research and writing process, several AI tools were used to enhance efficiency and precision. Scopus AI assisted in refining the literature search strategy. Claude Opus 4.1 was employed to refine sentence structure and enhance clarity. All AI-assisted outputs were carefully reviewed and edited by the authors to ensure accuracy and integrity.

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