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Review article

A road map for developing novel decision support system (DSS) for disseminating integrated pest management (IPM) technologies

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ABSTRACT

Integrated Pest Management (IPM) technologies offer effective solutions to reduce the negative effects of crop pests while considering human and environmental health. However, disseminating these technologies faces several barriers, with one of the most significant being the lack of farmer awareness regarding their availability, deployment, and uptake. Digital tools are perceived as a new form of leverage for overcoming these barriers. This study analyzes current IPM digital tools and their potential to boost farmers' awareness of the deployment and adoption of IPM technologies. From a software engineering perspective, this study aims to emphasize the critical functionalities and limitations of various IPM dissemination tools. It provides valuable insights to improve the adoption process and streamline the dissemination of IPM technologies. Through a systematic search in Google, Scopus and Web of Science for journal articles, over 32 dissemination tools were identified. The study thoroughly assesses these tools and identifies 5 main limitations hindering their regular use, especially in developing countries. Among the most significant limitations are the inadequate representation of tools developed in developing countries, lack of agroecological customization, and insufficient offline functionalities. Building on these findings, a user-centered design is employed to propose a software architecture for a novel Decision Support System (DSS) tailored to farmers and experts. The architecture comprises a local database for offline access, a mapping engine for data visualization, a conversation module with a triangulation engine for knowledge sharing, and an agroecology engine for technology recommendation based on an agroecological classification of the user's landscape. Drawing from the review, identified limitations, and the proposed architecture, we illustrate how the resulting novel DSS is anticipated to improve the dissemination of IPM technologies.

1. Introduction

Food security remains one of the most significant challenges of the 21st century, affecting approximately 20.2 percent of the African population (UNICEF et al., 2022). Achieving food security is also essential for meeting the Sustainable Development Goals (SDGs), including "No Poverty", "Zero Hunger", "Good Health and Well-being", promoted by the United Nations for the prosperity of people and the planet (UN, 2015). However, the complexity of addressing this challenge is increasing due to factors such as population growth, climate change, and food losses caused by pests. Pests have a widespread impact on agriculture, with billions of dollars lost every year due to the devastation of crops and fruits by various insects, such as the *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae), and *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) (Khan et al., 2018; Niassy et al., 2022; Agboka et al., 2022).

Owing to their immediate effectiveness, chemical pesticides are one of the most prevalent methods employed by farmers to control these pests. Unfortunately, the overuse of such agrochemicals negatively impacts human health and has disastrous environmental effects such as water and air contamination, soil fertility degradation, and elimination of non-targeted organisms (such as bees and parasitoids) (Aktar et al., 2009; Nicolopoulou-Stamati et al., 2016). As a result, innovative approaches to pest management that are more sustainable and

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environmentally friendly are in demand. One of the most promising approaches is Integrated Pest Management (IPM). This concept refers to a holistic and sustainable pest management approach using ecological, biological, physical, and reasonable chemical strategies to bring the pest population below the economic injury level. The IPM strategy, which includes a range of tactical and ecological processes known as IPM technologies, is based on a thorough understanding of pest behavior, biology, and ecology (Stenberg, 2017; Deguine et al., 2021; University of Illinois Extension, 2021). Several IPM technologies are currently in use worldwide, each addressing one or more specific aspects of pest management, including prevention, monitoring, and control. These technologies are usually classified into four main categories, i.e., biological, chemical, cultural, and mechanical, encompassing habitat manipulation, resistant varieties, and biotechnological tools (Frank et al., 2022).

Although IPM technologies have many advantages, their adoption still faces significant barriers. One of the most significant barriers is the lack of awareness among farmers regarding the availability, deployment, and uptake of these IPM technologies (Deguine et al., 2021). One solution to this diffusion problem is the concept of *technology delivery* (Kroschel et al., 2012; Wyckhuys et al., 2018). Among the main components of technology delivery, there are *dissemination techniques*. They encompass a range of tools designed to disseminate and present information regarding the application of IPM technology to diverse end-users, such as farmers, private sector stakeholders, and the general public. *Field days*, *extension agent visits*, and *farmer field schools* (FFS) are some examples of IPM dissemination techniques (Harris, 2011). With the rise of Information Technology (IT), more modern dissemination techniques such as mass media, websites, and web and mobile applications have also been developed. One of the challenges with the current dissemination techniques is that they pay little attention to the ecology and ecological functioning of the agroecosystems in which the technologies are deployed (Deguine et al., 2021).

Several studies have highlighted that the local agricultural context is one of the factors most related to the low adoption of a specific IPM technology in a defined area (Rajotte et al., 2005; Deguine et al., 2021). Indeed, the local agricultural context strongly influences three critical elements associated with successful technology deployment: *availability*, *awareness*, and the *suitability* of this technology for a targeted area (Rajotte et al., 2005). The suitability of an IPM approach is the factor that requires the uttermost attention in this study. In fact, according to Rajotte et al. (2005), Kogan et al. (2007) and Wyckhuys et al. (2018), a specific technology may not be suitable for a specific area despite all the efforts made by farmers and experts. This is justified by the fact that suitability is influenced by different parameters such as the expected level and variability of yield, the cost of inputs, or the agroecological factors such as the soils, nutrients, sunlight, and coexisting organisms of the targeted region. Failure to incorporate these parameters can result in situations where the implementation of the technology is perceived as either a partial or complete failure. For example, in Gurr et al. (1998), the authors demonstrated that the deployment of "habitat management" technology in an area without taking into account its agroecology might create a habitat that is excessively favorable to natural enemies. Consequently, their inclination to disperse and feed on adjacent crops becomes ineffective. Another example is provided by Lu et al. (2013, 2015), who showed that climate change can have harmful effects on the behavior of biological agents, including their inability to overwinter during biological control application and the risk of attacking non-target species. These examples highlight the need to develop an innovative dissemination approach depending on factors that can lead to a better decision-making process for IPM technologies in a specific area.

The paper addresses the following research questions:

Q1. What are the key functionalities and limitations of current IPM dissemination tools, particularly the decision support systems?

Q2. How can we design a user-friendly, context-aware decision support system to improve the dissemination of IPM technologies, especially in developing countries?

Q3. What recommendations can be provided to enhance the suitability and dissemination rate of future IPM dissemination tools, and what challenges need to be addressed in this regard?

This paper, from a software engineering perspective, reviews existing IPM dissemination tools and then applies a user-centered design to propose a conceptual framework for improving delivery processes. The proposed framework will assist those new to the dissemination of IPM technologies in identifying gaps in the existing literature, particularly regarding the limitations of current dissemination tools. Furthermore, it will serve as a road map for the development of new and improved strategies to enhance the dissemination processes of IPM technologies. Additionally, this study aims to enhance the interdisciplinary collaboration between agriculture and computer science fields, ultimately leading to the development of more effective and sustainable pest management tools.

This article is organized as follows. Section 2 provides background information on IPM and technology delivery. Section 3 gives a step-by-step explanation of the systematic methodology used in this study. Section 4 presents the definition, functioning, and limitations of the reviewed IPM dissemination tools. Section 5 presents the discussion, and Section 6 describes the design of a new DSS that integrates agroecological factors into the diffusion of IPM technologies. Finally, Section 7 presents the conclusion.

2. Definition of concepts

2.1. Integrated pest management

Integrated Pest Management lacks a standardized definition, with over 100 different definitions put forth by researchers (Deguine et al., 2021). However, most of these definitions converge on four core principles (Stenberg, 2017; Deguine et al., 2021):

- Integration of techniques to achieve effective and sustainable pest management.
- Socio-economic viability to reduce the use of chemical pesticides, minimize adverse environmental and human health impacts.
- Optimization of nature-based solutions allowing the use of natural pest control measures to minimize adverse effects on the agroecosystem.
- Employs chemical pesticides only as a last resort when other pest control measures have failed to achieve the desired results.

When carefully combined, IPM technologies suppress the pest populations in an environmentally and cost-effective manner that generates higher yields and fruits that are pest and chemical-free (Niassy et al., 2022). The success of IPM relies on the fact that the various tactics target several stages of pests. Therefore, IPM can be defined as a holistic and sustainable approach that incorporates multiple pest management techniques while promoting socio-economic viability and employing chemical pesticides as a last resort.

According to the PAMS framework, IPM involves four key components: prevention, avoidance, monitoring, and suppression (Oregon State University, 2022). Prevention consists of implementing tactics to keep potential pests from entering an area or inhibit their spread to new areas. Avoidance involves creating inhospitable conditions and limiting resources to make life challenging for pest organisms if they are already present or expected annually. Monitoring involves regular inspection and sampling to determine the presence and abundance of pests and assess control measures' effectiveness. Suppression is achieved through a combination of mechanical, physical, and cultural control methods (see Fig. 1). Mechanical and physical control consists of using physical

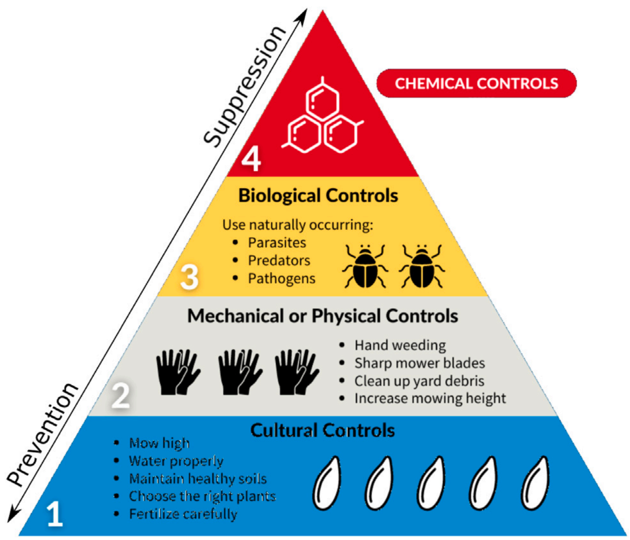

Fig. 1. Summary of Integrated Pest Management (IPM) control methods adapted from University of Illinois Extension (2021).

methods (traps, nets, barriers) to create an unfavorable environment for pests. Cultural control involves modifying the crop environment by implementing practices such as changing irrigation or fertilization, crop rotation, or intercropping to make it less favorable for pests to thrive (Ferro, 2002; Russell, 2019). Biological control relies on natural enemies of pests, such as predators or parasitoids, to regulate their populations (Stenberg et al., 2021). Chemical control involves using pesticides, but only when necessary and in a targeted manner.

2.2. Technology delivery and dissemination of IPM technologies

The concept of "technology delivery" varies depending on the research discipline and purpose. In IPM, it involves processes for translating, packaging, and upscaling IPM technologies to increase their adoption among farmers and end-users. Dissemination is pivotal in this context, as it is defined as the process of communicating an innovation through specific channels within a social system over time (Rogers, 1995). This study refers to dissemination tools as communication channels and materials used to convey information about IPM technology to diverse end-users, including farmers, private sector actors, and the public. Lately, two primary dissemination tools have been widely used in the field of IPM: Farmer Field School (FFS) and ICT tools. Both prioritize farmers-centered interactions, making them highly effective for reaching end-users, especially smallholders (Harris, 2011). The subsequent sections provide an overview of these two dissemination tools.

2.2.1. Farmer field schools

Developed in the late 1980s by FAO in response to brown rice leafhopper outbreaks in Indonesia (Van de Fliert et al., 1995), FFS is undoubtedly one of the most effective tools for disseminating IPM technologies in general and biocontrol technologies in particular. In the context of biocontrol, FFS consists of a grouping of 15 to 25 farmers who frequently meet in a participatory and experiential manner throughout the farming season. FFS's core objective is to empower farmers with knowledge and skills to make informed decisions in pest management, using environmentally friendly and economically viable approaches. It emphasizes on farmer-to-farmer knowledge sharing, encourages critical thinking, and promotes the adoption of IPM strategies tailored to local conditions (Wyckhuys et al., 2018; Nations, 2020).

The principle of biocontrol FFS is built upon the Agro-Ecosystem Analysis (AESA). It is a system of analysis through which farmers

Table 1
Eligibility criteria for review, focusing on IPM decision support systems.

Inclusion criteria	Exclusion criteria
- Articles proposing an architecture or an implementation of DSS among its contributions - The proposed DSS must include smallholders among its end users - Presence of terms related to IPM - Presence of terms related to technology delivery and/or dissemination - Presence of terms related to biological and/or cultural control	- Articles that are not written in English - Reviews that do not propose a new tool to improve IPM dissemination process - Articles providing unclear results or findings about the functionalities of the proposed tool - Duplicated studies

initially observe the crops and then take note of soil conditions, water levels, and the presence of pests, natural enemies, diseases, or weeds. Each group's AESA report is then shared with the other groups to stimulate discussion on topics that will lead to re-enforcement and learning of new concepts. "Learning by doing" is the core of the whole FFS learning process. Thus, growers can often observe the predation mechanism of collected insects through insect zoos to conceptualize food webs or observe insecticides' effects on natural enemies in small field plots (Wyckhuys et al., 2018). All these processes, supported by the AESA, directly and substantially improve farmers' decision-making process when applying a biocontrol technology.

The use of FFS as a dissemination tool for biocontrol technologies has resulted in several successes in controlling pests in tropical areas ("backwardness" of these areas in terms of biocontrol advances). One successful outcome is the control of tomato leafminer (*Tuta absoluta*) by growers in North Africa after the deployment of a large FFS campaign (Fredrix, 2014). Another successful case is the control of FAW (Fall Armyworm) in Africa through the conservation of its natural enemies, thanks to an extensive campaign initiated by FAO in 2018 (FAO, 2018).

2.2.2. Information communication technology (ICT) tools

In this study, ICT tools refer to a set of digital tools (websites, web and mobile applications, software) developed to assist an actor in learning and mastering an IPM technology. The dissemination of IPM technologies usually involves a process of co-creating knowledge, as discussed in Section 2.2.1. In this process, farmers acquire, interpret and integrate information from different sources, including training, other farmers, and personal experiences developed during previous campaigns. The advent of ICT tools (and their high penetration rate in enclave areas) provides a favorable condition to play a significant role in the diffusion process of IPM technologies (Wyckhuys et al., 2018; Deguine et al., 2021). Among these tools, the primary emphasis lies on the DSS, followed by ICT learning platforms and visual materials.

Generally, Decision Support Systems (DSS) are defined as interactive computer systems that help decision-makers to use existing data, model, and solve unstructured problems (Guimapi et al., 2020). These systems play a crucial role in today's world due to the complexity associated with decision-making, given the tremendous amount of information that can come from various sources such as raw data, documents, personal knowledge, and/or models. At the beginning of the development of DSS in the 1960s and 1970s, their primary focus was on streamlining structured decisions in business contexts (Zhengmeng and Haoxiang, 2011). However, as technology advanced, the scope of DSS applications expanded to encompass diverse sectors, where they have been instrumental in revolutionizing decision-making processes by providing data-driven insights and informed choices to optimize productivity, sustainability, and resource utilization. This evolution reflects how DSS have evolved to address the intricate decision-making challenges faced by different industries, including agriculture and the specific domain of IPM (Jones et al., 2017). In the context of IPM, these tools are essential for technology dissemination in the sense that they provide helpful information to farmers (weather data, soil data, imagery) and assist them in various decisions such as crop selection, the choice of biopesticides, the choice of IPM technology to apply and many others.

ICT learning platforms are online educational platforms that provide interactive learning experiences to users. In the context of IPM, these platforms can offer farmers and other end-users a convenient and accessible way to learn about IPM practices and technologies (Wyckhuys et al., 2018). They can provide various interactive learning resources, such as videos, webinars, and online courses, which help end-users to acquire the knowledge and skills needed to implement IPM practices effectively.

Visual materials, such as posters, brochures, and diagrams, are also effective tools for disseminating information about IPM technologies (Peshin et al., 2014). These materials communicate key messages and concepts about IPM in a clear and accessible manner. For instance, posters and diagrams can illustrate the life cycle of a pest or the process of implementing a particular IPM practice, while videos can explain complex concepts related to biological control technologies (Wyckhuys et al., 2018).

Overall, ICT tools are powerful tools that can enhance the dissemination of IPM technologies and help end-users to implement them successfully.

3. Methodology

This section outlines the methodology employed to select IPM dissemination tools, which adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement (Moher et al., 2009).

3.1. Eligibility criteria

Table 1 outlines the eligibility criteria on which this review was based. Two additional criteria were considered to determine which studies should be included or excluded. The first criterion was to target studies presenting web-based DSS. This was justified by the accessibility and affordability of web-based DSS, which are easily accessible from anywhere with an internet connection and have lower costs than traditional tools requiring specialized hardware and software. To our knowledge, this study is the first to target web-based IPM DSS since Damos (2015), which is nevertheless considered one of the most accessible ways to disseminate technologies due to the high penetration rate, availability, and accessibility rate of ICT tools in different regions around the world (Andres et al., 2019). The second criterion was to target studies presenting dissemination tools providing functionalities related to natural biological and cultural controls owing to the assumption that smallholders commonly use these control methods without depending on the availability of biofertilizers, fertilizers, and mechanical traps (Gabryś and Kordan, 2013).

3.2. Search strategy

This review spans an in-depth literature analysis up to April 2023, using bibliographic data sources. The two leading electronic databases for searching peer-reviewed articles, Scopus and Web of Science (Mongeon and Paul-Hus, 2016), were employed for this purpose. These databases were selected based on their ability to provide full-text access to the most important peer-reviewed journals and conference proceedings on computer sciences applied in agriculture. The Google Scholar facility was also used to cross-check the findings and citations and to locate other papers in less well-known libraries. The selection of these databases aimed to ensure access to the most relevant and up-to-date literature on the topic.

A bibliographic search was conducted using search terms for six concepts in the article's title, abstract, and keywords: (1) Decision Support System was represented as (“decision support” OR “decision-support” OR “decision-making” OR “decision making” OR “knowledge-based”), (2) end users were coded as (“farmer*” OR “grower*” OR “smallholder*” OR “producer*”), (3) IPM was coded as (“Integrated pest management” OR “pest management” OR “pest control”), (4) dissemination was coded as (“dissemination” OR “diffusion” OR “transfer” OR “extension” OR “recommend*” OR “suggest*” OR “adopt*” OR ”broadcast*”), (5) biological control was coded as (“biological *” OR “threshold” OR “parasitoid” OR “natural enemies” OR “beneficial insects”), (6) cultural control was coded as (“crop rotation” OR “intercropping” OR “irrigation” OR “weed management”).

Table 2
Keywords used in database searches in review.

Key concepts	Related terms
Decision support system	"decision support" OR "decision-support" OR "decision-making" OR "decision making" OR "DSS" OR "knowledge-based"
End users	"farmer*" OR grower* OR "smallholder*" OR "producer*"
IPM	"Integrated pest management" OR "pest management" OR "pest control"
Dissemination	"dissemination" OR "diffusion" OR "transfer" OR extension" OR "recommend*" OR "suggest*" OR adopt*" OR broadcast*
Biological control	"biological *" OR "threshold" OR "parasitoid" OR "natural enemies" OR "beneficial insects"
Cultural control	"crop rotation" OR "intercropping" OR "irrigation" OR "weed management"

Table 2 summarizes the review's key concepts and the related search terms used to search them in the different bibliographic databases. The final search queries used in each database are listed below:

> **Scopus:** *(TITLE-ABS-KEY(“decision support” OR “decision-support” OR “decision-making” OR “decision making” OR “knowledge-based”) AND TITLE-ABS-KEY(“farmer*” OR “grower*” OR “smallholder*” OR “producer*”) AND TITLE-ABS-KEY(“Integrated pest management“ OR ”pest management” OR “pest control”) AND TITLE-ABS-KEY(“dissemination” OR “diffusion” OR “transfer” OR “extension” OR “recommend*” OR “suggest*” OR “adopt*” OR “broadcast*”) AND (TITLE-ABS-KEY(“biological *” OR “threshold” OR “ETL” OR “parasitoid” OR “natural enemies” OR “beneficial insects”) OR TITLE-ABS-KEY(“crop rotation” OR “intercropping” OR “irrigation” OR “weed management”)))*
> **Web of Science:** *TS = (“decision support” OR “decision-support” OR “decision-making” OR “decision making” OR “knowledge-based”) AND TS = (“farmer*” OR “grower*” OR “smallholder*” OR “producer*”) AND TS = (“Integrated pest management” OR “pest management” OR “pest control”) AND TS = (“dissemination” OR “diffusion” OR “transfer” OR “extension” OR “recommend*” OR “suggest*” OR “adopt*” OR “broadcast*”) AND (TS = (“biological*” OR “threshold” OR “ETL” OR “parasitoid” OR “natural enemies” OR “beneficial insects”) OR TS = (“crop rotation” OR “intercropping” OR “irrigation” OR “weed management”))*

3.3. Screening and selection

The screening and selection process is presented in Fig. 2. As can be seen, the search in Scopus and Web of Science retrieved 340 documents. The screening was performed in two stages according to the PRISMA guidelines: (1) initial screening by title and abstract and (2) full-text screening. Both databases were screened together, and the criteria listed in Table 1 were used to include or exclude the retrieved articles. The initial screening based on title and abstract excluded 288 articles, some of which were not in English (n = 9), some of which were not focused on the delivery of a DSS (n = 220), and some of

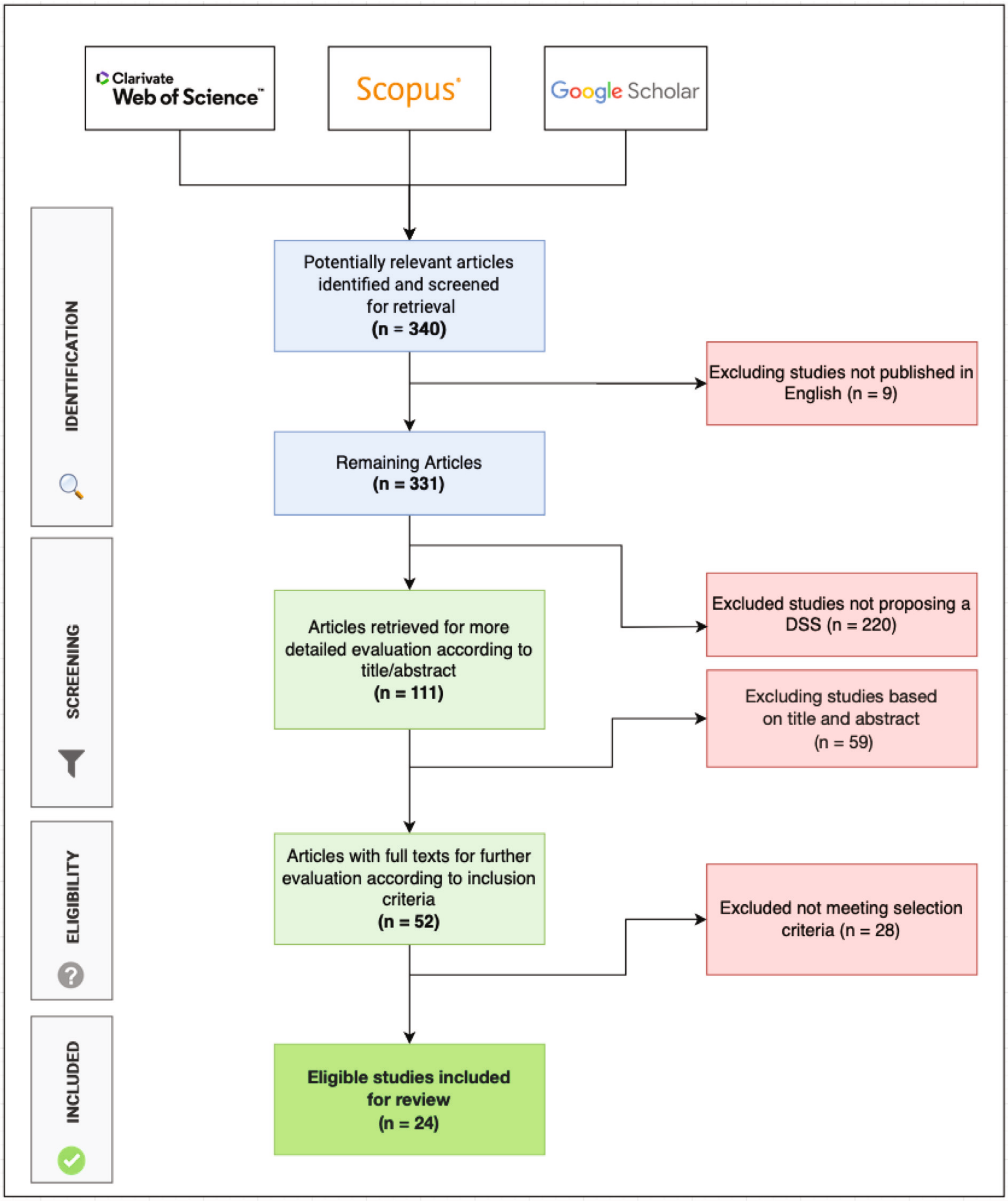

Fig. 2. Selection process of decision support systems for IPM dissemination.

which did not meet all the inclusion criteria based on the title and abstract simultaneously (n = 59). Fifty-two papers were selected for full-text screening, focusing on identifying a clear presentation of the software architecture of a web-based DSS aimed at improving the dissemination or application of an IPM technology. Papers focusing mainly on mathematical aspects, such as threshold development or modeling, with less emphasis on software engineering aspects, such as DSS design and development, were excluded. In addition, some papers did not pass the assessment, either because the presentation of the tool was ambiguous or because the tool was not accessible online, making further investigation difficult.

Of the 52 papers, 28 were excluded, leaving 24 papers that met all the criteria for identifying IPM dissemination tools. Each of these 24 papers contains at least one section dedicated to designing or presenting a web-based DSS to improve the dissemination of one or more IPM technologies. In addition to the bibliographic search, a complementary Google search identified 8 additional platforms focused on IPM technologies. As many tools of interest are not documented in the academic literature, we acknowledge that searching tools on Scopus and Web of Science might be limited. Therefore, the supplementary Google search approach was pivotal in expanding our research scope to cover a total of 32 IPM dissemination tools.

3.4. Approach

Our approach draws inspiration from the study presented in Damos (2015) on IPM tools, particularly focusing on the pivotal role of thresholds in biocontrol tools and the modeling methods used in cultural control tools. While the author expertly recognized these as crucial elements influencing IPM DSS, our approach goes beyond by conducting a more profound technical analysis, scrutinizing these DSS tools through a software engineering lens. This includes an investigation into the software architectures, programming languages, and frameworks underpinning these tools, providing a holistic understanding that encompasses not only their theoretical effectiveness but also their practical implementation, scalability, and potential for future enhancements.

4. Results

In this section, we diligently delve into addressing the first research question outlined in Section 1 of this study. This endeavor involves a comprehensive exploration and presentation of the fundamental underpinnings, functionalities, and inherent limitations associated with these IPM tools. This presentation is structured according to the PAMS framework described in Section 2.1.

4.1. Prevention

According to our bibliographic research, the dissemination of IPM prevention strategies frequently relies heavily on ICT-based learning platforms and visual resources.

In the realm of ICT-based learning platforms, several offer valuable resources such as pest data, seasonal alerts, field identification, distribution maps, fact sheets, and publications for specific regions or globally (Barratt et al., 2018). Among these, the *Plantwise web* platform,[1] developed by the Centre for Agriculture and Bioscience International (CABI), stands out for its commendable impact within the scientific community. Plantwise empowers extension agents to swiftly and accurately diagnose crop pests and diseases, enabling farmers to implement effective IPM strategies (Zhang and Chaudhary, 2021). Another notable web platform is *Eurowheat.org*,[2] designed as a comprehensive resource for aggregating, analyzing, and disseminating vital information concerning wheat disease management in European Union (EU) member states within an IPM context (Jørgensen et al., 2014). It equips farmers with essential insights into wheat disease occurrences, prevention methods, and disease differentiation. Eurowheat.org encompasses two vital sections, "Pathogens" and "Fungicide Resistance", dedicated to biological pest control in wheat crops. The dissemination of technology through ICT tools is becoming increasingly popular with the development of other web-based platforms moving in the same direction as *Plantwise*. These include *AgPest* (Tozer et al., 2017), *COLEAD Training*,[3] *IOBC-WPRS Pesticide Side Effect Database* (Jansen, 2013), and many others.

Regarding the visual materials (brochures, diagrams, and videos), the rise of ICT facilitated by the proliferation of mobile phones, computers, and tablets has substantially enhanced self-learning processes. Visual materials address the challenge faced by growers in comprehending abstract concepts that lack tangible representation. This challenge may arise due to the intricacies of certain prevention strategies, necessitating visual familiarity with natural enemies and a moderate grasp of agroecological concepts associated with these technologies. As a result, printed materials, videos, and other visual resources have emerged as practical tools for disseminating biocontrol technologies (Peshin et al., 2014; Wyckhuys et al., 2018). Pioneering studies, like the one conducted by Van Mele et al. (2005), have harnessed videos as a means of imparting knowledge to farmers. In this case, Bangladeshi farmers were trained in innovative, sustainable rice seeding methods, which significantly contributed to promoting IPM prevention through educational films, animated cartoons, and movies. The success of these efforts has sparked numerous projects, including the production of videos aimed at promoting various IPM technologies. For instance, the Breeding Invertebrates for Next Generation BioControl[4] (BINGO) project (Leung et al., 2020) focuses on enhancing natural biocontrol through genetic variation for breeding, monitoring, and performance improvement of natural enemies. In 2019, the project produced two educational videos for farmers and extension agents. Another noteworthy initiative is the Scientific Animations Without Borders (SAWBO) Deployer Application (Bello-Bravo et al., 2018), developed by Michigan State University, which offers a wealth of free educational videos on various prevention techniques applicable in the field.

The primary challenge in disseminating IPM technologies through ICT tools lies in ensuring equitable access conditions. These conditions encompass four aspects outlined by Wyckhuys et al. (2018): (1) motivational access (referring to farmers' motivation to use the tool consistently), (2) material access (availability of digital equipment and a reliable internet connection), (3) skill access (the farmer's ability to operate digital equipment effectively), and (4) use access (allocated time for usage). Fulfilling all these conditions is crucial to ensure an optimal learning experience in acquiring the targeted technology. Unfortunately, these conditions are not always guaranteed, especially in certain developing tropical regions where internet access is either nonexistent or severely limited.

4.2. Avoidance

4.2.1. Decision support systems

Numerous studies propose the use of DSS to optimize and disseminate IPM avoidance tactics (Phoksawat et al., 2019; Lagos-Ortiz et al., 2020; Pahmeyer et al., 2021). These DSS prove invaluable in tasks such as data collection and analysis (including climate, crop growth, and pest populations), crop selection, technology evaluation, and land suitability assessment. The principles and modules of these DSS typically align with the specific technologies they serve. For example, in crop rotation, some DSS employ linear programming models based on weather data, remote sensing, and other sources. Conversely, other crop rotation DSS leverage machine learning algorithms, analyzing historical crop data to offer crop rotation recommendations based on their analyses.

In the first case, we have the "Fruchtfolge" web tool (Pahmeyer et al., 2021), which utilizes a mixed integer linear programming (MILP) model. This model factors in soil type, quality, previous crop effects, and monthly work hours of farmers. The tool developed with Node.js on the server side, and JavaScript on the client side adopts a three-tier architecture (see Fig. 3). The presentation layer encompasses login, data input, and results pages, while the application layer houses the linear programming engine responsible for computation and decision-making. The persistence layer consists of one database that connects to five external data sources through three Application Programming Interfaces (APIs). The architecture of Fruchtfolge prioritizes efficiency through modularity and interoperability, thanks to its three-tier design and developed APIs. However, the tool's usability is currently limited to the German language.

In the second case, a Seq2Seq-LSTM (Sequence-to-Sequence Long Short-Term Memory) methodology (Dupuis et al., 2023) is employed. This approach utilizes a recurrent neural network (RNN) model to forecast the most probable crop rotation scenarios to be implemented

[1] https://plantwiseplustoolkit.org/.
[2] https://agro.au.dk/forskning/internationale-platforme/eurowheat.
[3] https://training.colead.link.
[4] https://www.bingo-itn.eu/.

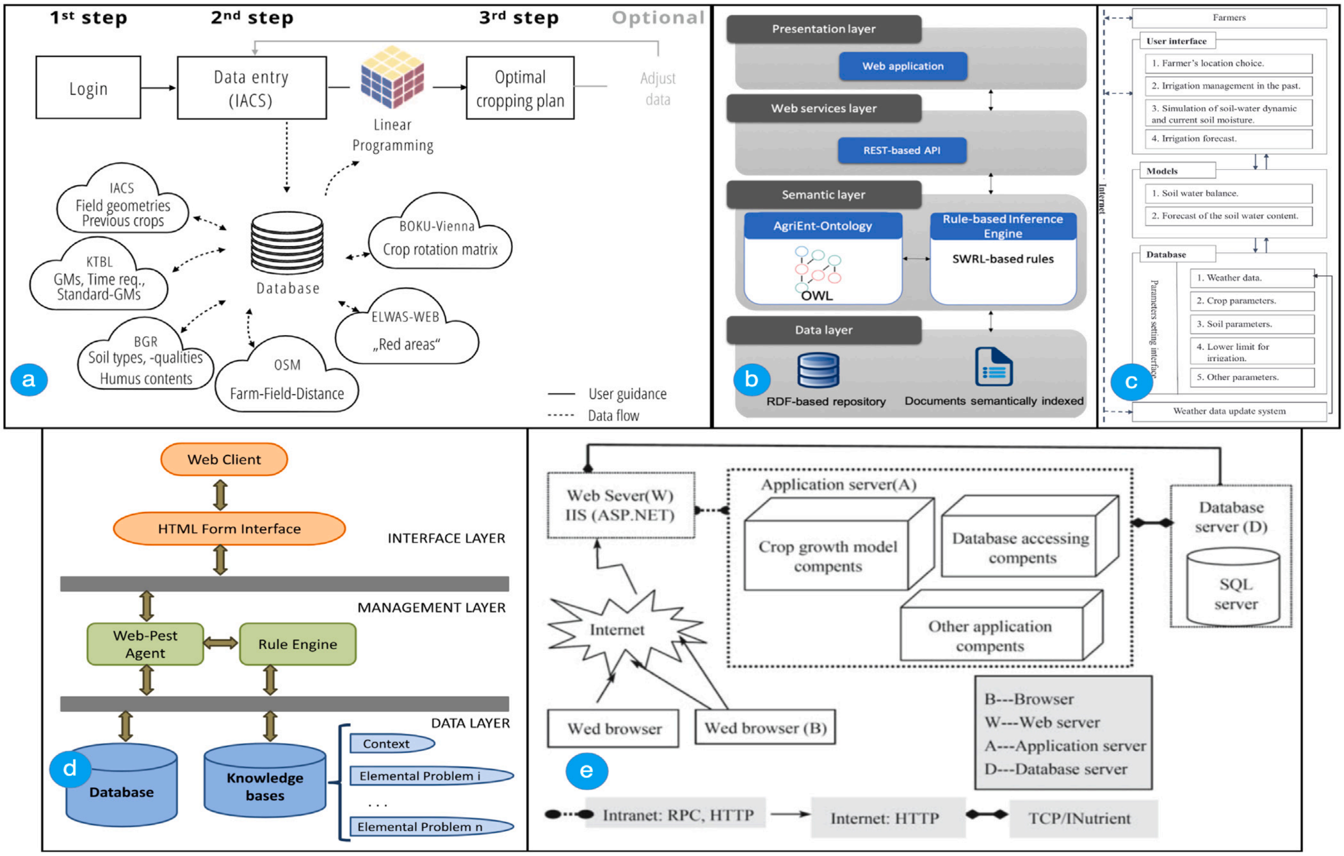

Fig. 3. Software architecture of five reviewed tools extracted from their respective literature sources (a) Fruchtfolge (Pahmeyer et al., 2021) (b) AgriEnt (Lagos-Ortiz et al., 2020) (c) WIDSSLI (Li et al., 2018) (d) Web-Pest (del Águila et al., 2015) (e) GMDSSCM (Zhu et al., 2007).

in a field during future growing seasons, taking into account historical crop patterns.

Intercropping also benefits from dedicated Decision Support Systems (DSS) employing various modes of operation. These include intercropping DSS based on crop simulation models derived from computerized mathematical representations of crop growth and others based on ontologies, i.e., vocabularies representing relationships between concepts or knowledge employing data structures, thus facilitating interoperability. DSS that integrated ontology-based solutions can maximize farmers' income (and minimize production costs) through an improved system of recommendation of the plants to be used in a specific area in case of intercropping. For instance, we have the ontology developed in Phoksawat et al. (2019) to improve the management of farmers' knowledge and provide reliable recommendations based on triangulated data from document analysis, experts, and farmers.

As ontology-based DSS, we can mention the AgriEnt (Lagos-Ortiz et al., 2020) web platform, which leverages expert knowledge of insect pests affecting Ecuadorian crops to provide decision support for crop pest management through a rule-based inference engine. AgriEnt follows a comprehensive four-tier architecture (see Fig. 3). The presentation layer encompasses essential components such as the login, diagnosis, and prevention pages. The web services layer features a REST-based (Representational State Transfer) API in charge of processing all the incoming requests. The semantic layer relies on an ontology and a rule-based inference engine. The ontology named "AgriEnt-Ontology", developed using Protégé (Knublauch et al., 2004) and Web Ontology Language (OWL), encapsulates knowledge regarding crops, diseases, symptoms, insects, insect pests, and treatment recommendations. The inference engine identifies crop disease causes through rules grounded in SWRL (Semantic Web Rule Language). Finally, the data layer houses a repository based on the Resource Description Framework (RDF), housing crop instances, and a semantically indexed collection of IPM-related documents.

It is worth noting that unlike prevention tools, many IPM avoidance DSS heavily rely on climatic factors like temperature, rainfall, and wind speed for precise recommendations. However, they often fail to adequately account for climate variability, which can impact their accuracy. Additionally, some of these tools require specific technical expertise, limiting accessibility for all farmers. Furthermore, many of these tools are very specific and may not address multiple concerns when combining different IPM technologies. User-friendly interfaces and effective marketing efforts upon public release are also areas where improvements are needed. Despite their potential benefits, farmers' everyday use of these DSS remains limited due to these challenges.

4.2.2. ICT-based learning platforms

While our bibliographic research revealed a wealth of ICT learning platforms focused on prevention tactics, there is a relatively smaller number dedicated to avoidance strategies. However, it is essential to develop such platforms as they can effectively promote recent technologies known for their innovative, participatory, sustainable, adoptive, or integrated nature. An example is push-pull technology (Khan et al., 2018), which involves a combination of different crop species and plants, making it more complex than other avoidance practices. To facilitate its adoption, ICT learning platforms are crucial. For instance, the "*icipe* PUSH-PULL[5]" website provides various modules, including pathways, dissemination materials, videos, and media, aiding farmers in implementing push-pull technology. On the mobile front, the "PUSH-PULL app" on the Google Play Store offers multiple learning

[5] http://push-pull.net/.

modules explaining the benefits and science behind push-pull, required materials, and many other features. In a broader context, the "Access Agriculture[6]" platform features several learning videos covering various technologies, such as crop rotation with vegetables, intercropping maize with pigeon peas, and intercropping pineapples with bananas and beans. Recent studies (Bentley et al., 2022) indicate that these videos have reached around 90 million people since the platform's launch in 2012, highlighting ICT's substantial role in disseminating IPM technologies, particularly avoidance methods.

As noted in Section 4.1, access to use and skills, as well as motivational and material access, remain the main challenges for dissemination through ICT-based learning platforms. These limitations, coupled with the disturbances caused by climate change and the often-weak focus of these platforms on agroecological compatibility, can easily lead to scenarios where their contents do not lead to the expected results. Therefore, it becomes crucial to couple these platforms with support tools that consider the local agroecological context of each farmer willing to implement the knowledge acquired on these platforms.

4.3. Monitoring

In many instances, DSS for monitoring typically consist of two integral modules, as noted in myFields.info (2016) and Rincon et al. (2023). The initial module serves the purpose of aiding in the identification of pests managed by the DSS, with some systems even extending this functionality to encompass the identification of the natural enemies of the targeted pests to promote a sustainable form of control. The second module, often referred to as the "Economic Threshold Calculator", is designed to calculate, utilizing established economic evaluation metrics and farmer-provided data, the pest population at which implementing an IPM technology becomes economically justified by equalizing the yield loss cost. This subsection will focus on the description of 2 DSS systems that incorporate the two modules, namely MyFields.info and AGROSAVIA web platform.

Myfields.info, as highlighted in myFields.info (2016) and Giles et al. (2017), stands as an accessible and forward-thinking web-based platform meticulously designed to seamlessly integrate biocontrol strategies within the framework of IPM DSS. Developed using the PhP framework Drupal, this innovative platform facilitates swift and precise detection and diagnosis of both local and regional pest infestations. It further extends its functionality to encompass proficient data management and summarization of pest occurrence records. The recommendations emanating from myFields.info are underpinned by data sourced from the Glance'n Go sampling method, encompassing critical metrics such as pest count, geographic location, damage severity, and the developmental stage of the affected plants. Regrettably, the architectural specificities of the software are notably absent within the referenced literature.

The AGROSAVIA web platform (Rincon et al., 2023) is an analog DSS designed for managing tomato leafminer (*Phthorimaea absoluta*) in greenhouse tomatoes. This tool is developed using the Shiny framework, a package created by Chang et al. (2023) for building interactive web applications with R. The software architecture of AGROSAVIA follows a two-tier layer approach, wherein the presentation layer harnesses HTML, CSS, and JavaScript, while the application layer leverages the computational prowess of R, prioritizing intricate computational processes while excluding persistent storage operations. AGROSAVIA's distinctiveness emerges from its dynamic evaluation of the action threshold, a computation grounded in real-time and cumulative control costs, potential yield estimates, and forecasts concerning tomato prices.

4.4. Suppression

With the advent of recent ICT advancements, a notable trend emerges: IPM suppression DSS are increasingly characterized by the presence of a module aimed at aiding farmers in the selection of the most suitable technology. This process is referred to as the IPM Pest Control Problem (IPM-PCOP or PCOP), which involves making decisions about IPM technologies for agricultural plots when pest activity surpasses established thresholds (del Águila et al., 2015; Cañadas et al., 2017). In the following text, we will introduce 3 tools that have been developed with this innovative feature.

The first tool, Web-Pest (del Águila et al., 2015), is a modular web knowledge-based system designed for PCOP support, enabling agricultural professionals to input crop observations. These data are then processed by an inference engine using backward chaining, i.e., an inference method that starts with the goal and works backward to find supporting evidence, suggests hypotheses, and evaluates rules in the system's knowledge base. Web-Pest recommendations consider factors such as the plot of land, sampling date, crop phenological stage, pathogen presence percentage, and beneficial fauna status. The software architecture of Web-Pest follows a three-tier layer design. The interface layer comprises web pages and a Common Gateway Interface (CGI) to interact with the underlying business logic. The management layer consists of a Web-Pest agent for the decision-making process and a rule-based engine for conducting reasoning and inferences. The rule-based engine is coded in C programming language. The persistence layer consists of two databases: one for storing the observations entered into the system and another for managing the knowledge representation.

The second tool, SAVIA (Cañadas et al., 2017), is a Java-based web platform that extends the PCOP metamodel from del Águila et al. (2015) for managing pests in table grapes. SAVIA aids in determining necessary treatments when pest action thresholds are met, primarily focusing on pest risk estimation to replace manual expert observation in crop management. Its innovation lies in the generation of its entire code through a Model-Driven Development (MDD) approach. This approach allows the specification of recommendation rules using Conceptual Modeling Language (CML), which undergoes model transformations to become a web and rule-based application. SAVIA follows a model-view-controller (MVC) pattern in its software architecture, employing Java Server Faces (JSF) and JBoss Rich Faces components for views and Java Expert System Shell (JESS) engines for controllers and models. This architecture promotes the separation of concerns and facilitates maintainability and extensibility but lacks a data persistence layer.

The third tool, Washington State University - Decision Aid System (WSU-DAS), developed by Washington State University and documented in Jones et al. (2010) for Washington tree fruit pest management, delivers pest and crop disease predictions, management recommendations, and a pesticide database with information on non-target effects (see Fig. 4). It employs a software architecture based on a MySQL database application, integrating weather data, insect and disease models, and pest status tracking based on physiological time. This design separates the interfaces from model subroutines, promoting ease of maintenance, interface customization, and language translation, including Spanish. Similarly, SOPRA (Samietz et al., 2011), a web-based tool for orchard pest control, integrates pest status and population prediction modules, recommends control measures, and considers local weather data such as solar radiation and temperatures. Unfortunately, detailed software architecture information for WSU-DAS and SOPRA remains unavailable in the existing literature.

While significant progress has been achieved in the realm of IPM DSS, several persistent limitations hinder their widespread adoption for disseminating suppression technologies. As observed in Rossi et al.

[6] https://www.accessagriculture.org/.

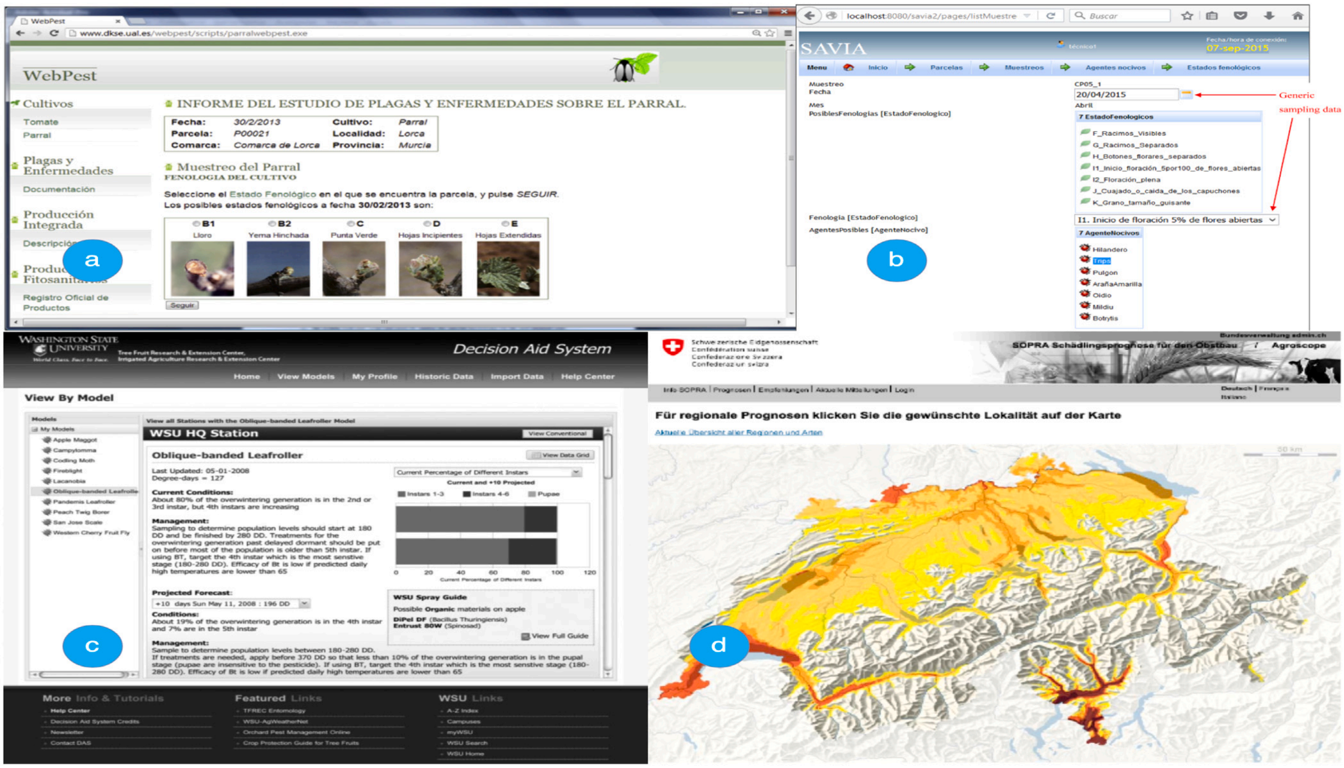

Fig. 4. Landing page of keys integrated pest management (IPM) decision support systems (DSSs) that integrate a module to assist farmers in selecting the most suitable IPM technology based on the results of the economic threshold evaluation (a) Web-Pest (del Águila et al., 2015), (b) SAVIA (Cañadas et al., 2017), (c) WSU-DAS (Jones et al., 2010), (d) SOPRA (Samietz et al., 2011).

(2012) and the examples discussed earlier, there is a prevalent tendency for most DSS to focus on addressing specific concerns, often limited to the control of singular pests. This approach often does not align with the complex realities faced by farmers, who frequently contend with multiple concurrent pest issues. Additionally, the lack of user-friendly interfaces poses a substantial barrier, given that many farmers possess limited computer literacy, becoming disoriented when confronted with intricate or non-intuitive tools. Further obstacles encompass the insufficient maintenance of DSS systems and the demand for lengthy and intricate input forms, particularly burdensome for basic users like farmers (Jones et al., 2010).

5. Discussion

The main objective of the last section was to address the first research question by providing a comprehensive analysis of the functionalities and limitations of the current web-based DSS for disseminating IPM technologies. In this section, we address the second research question by discussing the findings and features of the identified tools in order to provide guidelines for the implementation and adoption of these tools, especially in developing countries. In addition, the limitations of the reviewed tools are also discussed.

The first finding that can be extracted from the presented results is the insufficient representation of developing countries in the existing DSS. Fig. 5 shows that only 3 of the 32 evaluated tools (9%) are specifically intended for African users. A similar pattern is observed for South America, indicating that most digital IPM tools primarily target developed countries. This disparity may hinder the dissemination and adoption of IPM technologies in developing regions, which face unique challenges such as limited resources, different pest profiles, diverse cropping systems, and socio-economic complexities, necessitating customized solutions. In fact, many of the reviewed tools are not generic; they require adaptation to a specific context, including prevalent pests and diseases, cultivated crops, and the socio-economic circumstances of farmers. Additionally, integrating and processing live meteorological data into the DSS is also challenging and resource-intensive, especially when aiming at global coverage. These factors often lead researchers to focus on specific target areas to ease the development and deployment of the tools.

This observed disparity in tool distribution aligns with several studies, such as (Deguine et al., 2021), emphasizing the limited interest of the scientific community in creating dissemination tools that account for the specific local context of developing countries, which is crucial for enhancing adoption rates among smallholders. Furthermore, research like Baumüller (2018) and Quandt et al. (2020) have highlighted the positive impact of DSS on improving yields for smallholders in developing nations. Therefore, there is a pressing need to foster the development and dissemination of inclusive and accessible DSS for IPM technologies, catering to farmers and experts across all regions, particularly those in developing countries. It is also worth noting that the relatively fewer tools targeting Australia may be attributed to its more organized structure or smaller population in comparison to Africa or South America.

The second finding pertains to the recommendation logic employed by the reviewed tools in relation to IPM technologies. Fig. 6 shows that several reviewed DSS and platforms place minimal focus on agroecology, which is crucial in adopting a specific technology. Factors such as temperature, rainfall, latitude, altitude, landscape, and seasonality should be considered when suggesting an IPM technology to minimize the risk of failure during deployment. Approximately 60% (19 out of 32) of the reviewed tools offer static modules that overlook the agroecological context of the deployment location. Notably, 14 of these 19 tools are primarily designed for biological control. This observation aligns with a previous study by Giles et al. (2017), which emphasizes the necessity of a new paradigm that integrates various control strategies into IPM-based DSS tools. This finding underscores the pressing need for the development of new tools that can incorporate the local agroecological context into the recommendation process. Such tools

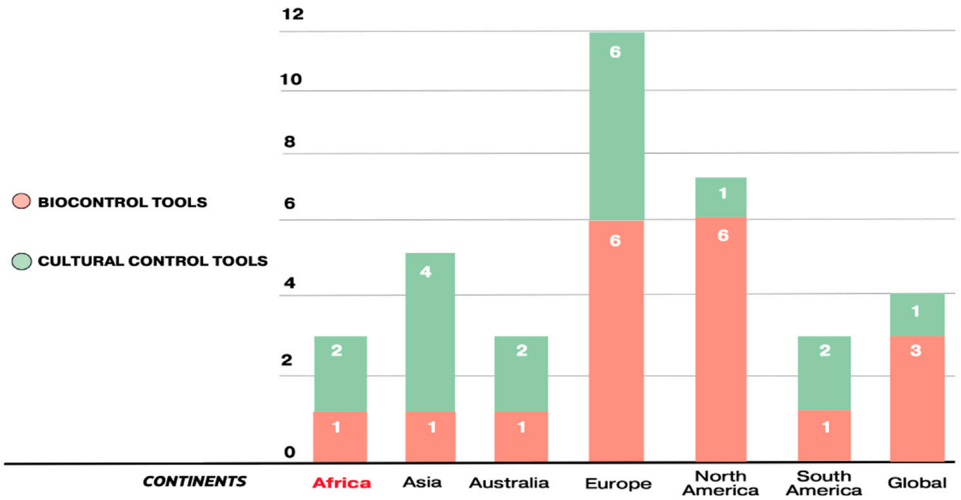

Fig. 5. Distribution of reviewed tools by targeted continents.

should move beyond static modules and embrace a more dynamic and adaptive approach that considers the diverse agroecological conditions in which IPM technologies are implemented.

The third finding of this study revolves around the usability and accessibility limitations present in the reviewed IPM tools. Some of these tools are overly complex, even for users familiar with digital technologies, and video-based platforms often lack subtitles in languages other than the primary one. These challenges in accessibility and usability are particularly pronounced in developing countries and can be attributed to three primary factors. Firstly, the low level of education among smallholder farmers, often accompanied by literacy challenges, hinders their effective use of digital tools (Adenle et al., 2015). Secondly, there is a prevalent lack of trust and confidence in these tools among farmers (Marinko et al., 2023). This is partly due to the “black-box” nature of some modules, which makes farmers reluctant to blindly adopt recommendations generated by these systems. Assuming these two factors can be addressed, the third critical aspect pertains to the absence of offline modes for farmers in remote areas. Fig. 7 reveals that a mere 15% (5 out of 32) of the reviewed tools incorporate offline functionalities, such as SMS recommendations, downloading learning resources, and utilizing local storage. Given the infrastructural challenges related to limited or no internet connectivity in developing countries, it is imperative to prioritize the development of tools with offline capabilities, thereby enhancing accessibility for users in remote areas. This finding underscores the importance of enhancing the usability and accessibility of IPM tools, particularly in regions with lower digital literacy rates and limited connectivity. Future tool development should focus on user-friendly interfaces, multilingual support, and robust offline functionality to ensure that these valuable resources are accessible to all, regardless of their location or digital literacy level.

In addition to the lack of accessibility and usability challenges, another crucial finding is that the majority of the reviewed IPM tools are proprietary. Only 2 out of the 32 tools studied (6%) are open source (see Fig. 8). This proprietary nature can have significant consequences, including limited adaptability, potential duplication of efforts, lack of transparency, and inefficiencies. This limitation also significantly impacts precision adaptability, an essential element in ensuring the suitability of IPM tools. Proprietary tools often come with restrictions that hinder their effectiveness, as they may not account for the diverse agricultural practices, pest profiles, climate variations, and soil types characteristic of different regions. In contrast, open-source tools provide the flexibility for experts and local communities to fine-tune the tools according to the specific conditions of their regions. Moreover, the proprietary nature of most IPM tools can lead to high costs and

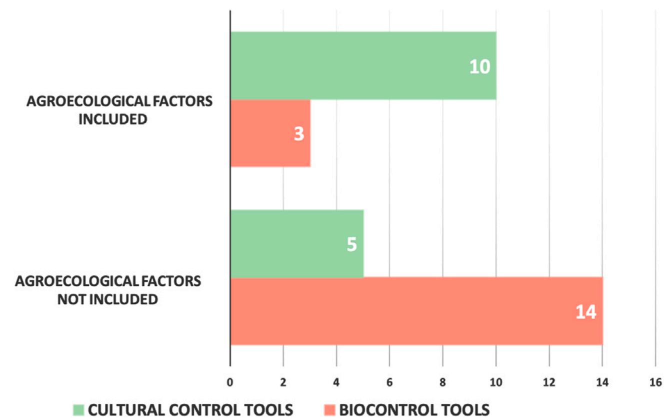

Fig. 6. Distribution of reviewed tools by agroecological factors for technology recommendation.

limited access, particularly for smallholder farmers in resource-limited settings. These limitations can hinder the adoption and effective use of IPM technologies by farmers and extension agents and impede collaboration and knowledge sharing within the scientific community. The emergence of social movements and communities, such as *“Farm Hack*[7]*”* and *“L’Atelier Paysan*[8]*”* showcases the potential of open-source agriculture technology in accommodating the specific needs of farmers (Giotitsas, 2019). These movements prioritize knowledge-sharing and collaboration among farmers to build and modify their tools, promoting adaptability, transparency, and low-cost solutions. Therefore, improving the effectiveness and impact of proposed digital IPM tools necessitates a focus on developing and disseminating more open and transparent tools, as well as promoting social movements and communities.

The final discovery from this study reveals a gap in user feedback and knowledge sharing in the reviewed digital IPM tools. Unlike the FFS approach, which prioritizes the creation and exchange of knowledge during and after the deployment of technology, only a meager 8% (3 out of 32) of the studied tools integrate chat functionalities. Incorporating chat functionalities in digital tools can offer numerous advantages, especially in developing countries. Firstly, it can foster

[7] https://farmhack.org/tools.

[8] https://www.latelierpaysan.org/English.

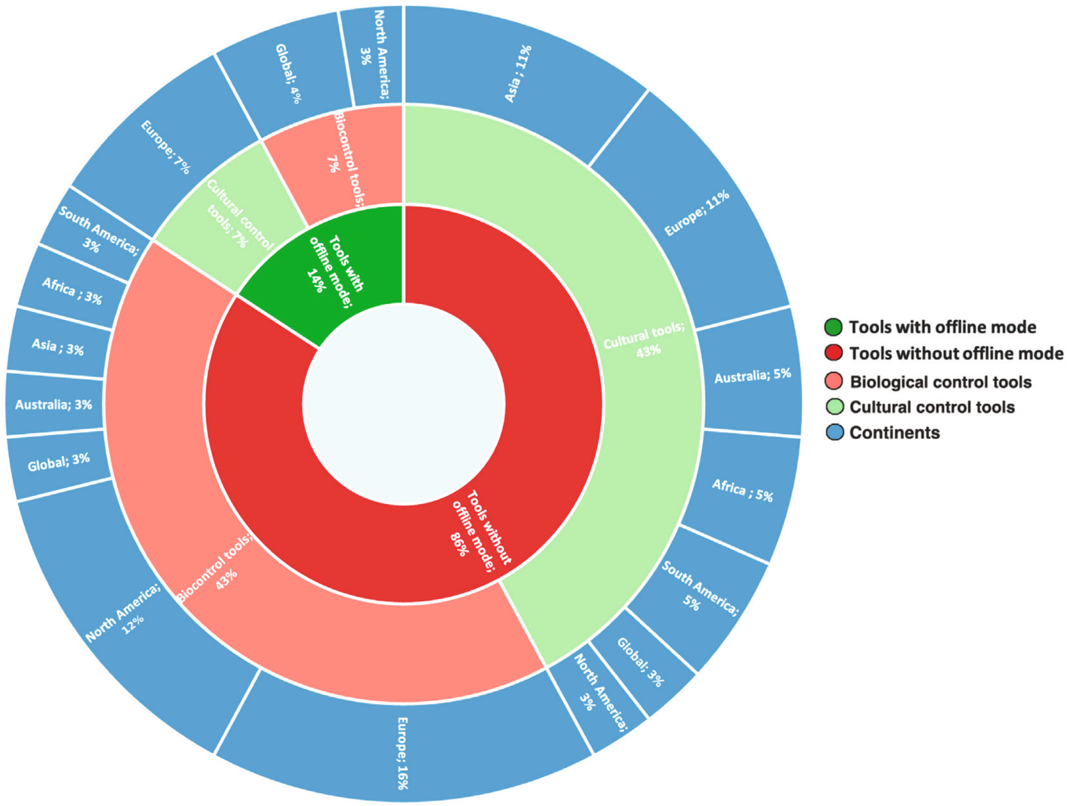

Fig. 7. Distribution of reviewed tools with and without offline mode.

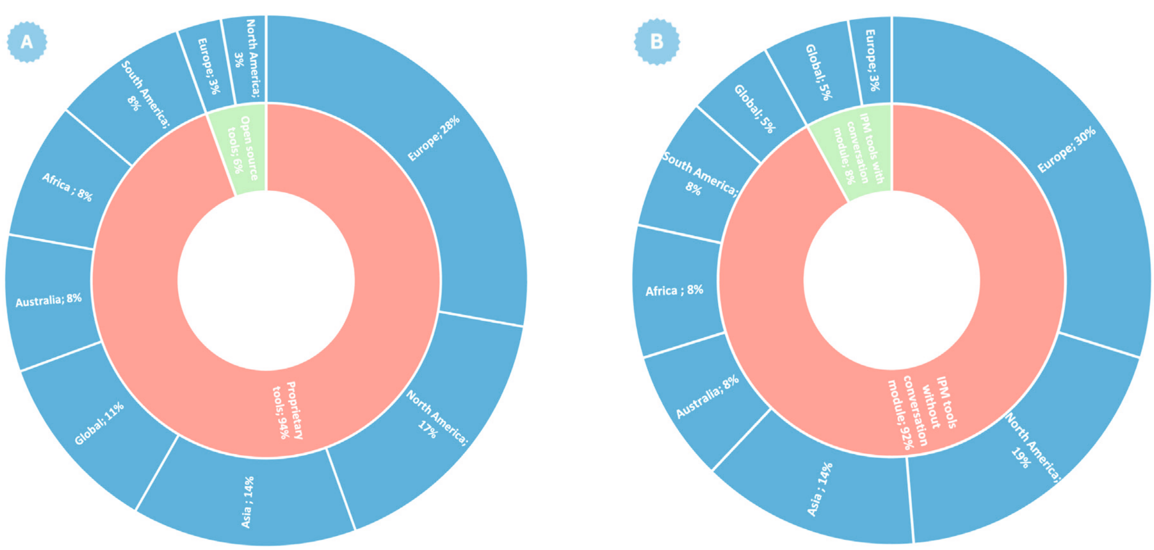

Fig. 8. (A) Distribution of reviewed tools by accessibility, (B) Distribution of reviewed tools by chat functionalities.

more user engagement and feedback, allowing farmers to share their levels of satisfaction and experiences and learn from one another. Secondly, it can promote knowledge and best practice sharing among farmers and extension agents, leading to more efficient IPM implementation. Thirdly, chat functionalities can offer farmers and experts a direct and personalized communication channel, providing real-time support and advice. Supporting this notion, Cieslik et al. (2021) demonstrated that incorporating ICT-mediated communication, such as chat functionalities, can lead to a statistically significant positive effect on cooperative behavior, disease control, returns on investment, and game winnings in the management of potato late blight in Ethiopia. Their qualitative analysis of voice chats provides evidence that farmers use ICT to facilitate coordination, establish collective norms, and manage reputation to increase trust. Hence, it is essential to underline the significance of integrating chat functionalities into digital tools for disseminating IPM technologies.

These findings emphasize the need to shift towards open-source models for IPM tools, enabling greater adaptability and affordability. Additionally, incorporating chat functionalities in digital tools can enhance user engagement, foster knowledge sharing, and provide real-time support, ultimately improving the effectiveness and impact of these tools in disseminating IPM technologies.

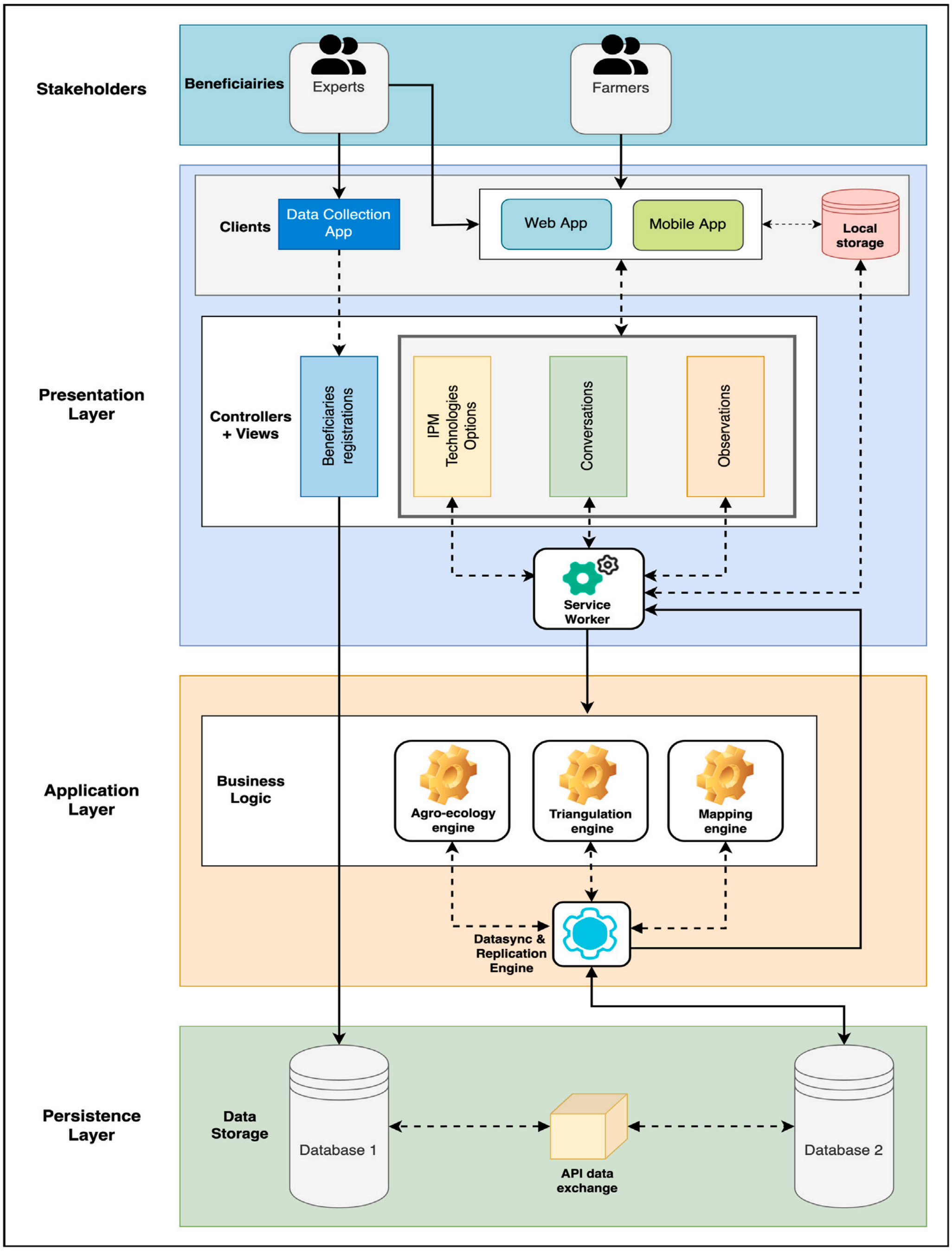

Fig. 9. Suggested improved DSS software architecture for the dissemination of IPM technologies.

6. A road map for developing novel DSS for disseminating IPM technologies

As discussed in the previous section, addressing the limitations associated with selecting, implementing, and adopting IPM technologies requires innovative DSS approaches. To this end, we propose a novel software architecture designed to overcome the five classes of limitations identified earlier. This architecture follows a user-centered design approach (Rose et al., 2018) and aims to provide comprehensive support to both farmers and experts, including IPM practitioners and extension agents. The DSS built upon this architecture will streamline various operations, including data collection, observation recording and visualization, real-time chat support, and IPM technology deployment advice. It is a three-tier architecture (see Fig. 9) designed to provide users with simultaneous support. Its user-centered approach accommodates a wide range of users with varying levels of digital proficiency. However, successful implementation hinges on addressing challenges such as user training, ensuring data quality, securing adequate resources, scaling to accommodate growing user bases, and customizing for different regions and languages. Ultimately, this architecture holds great promise in revolutionizing pest management practices by providing tailored IPM technology recommendations and fostering knowledge sharing and collaboration within the agricultural community. This section addresses the final research question by presenting the layers and components of the proposed architecture, as well as the challenges associated with its successful implementation and deployment.

6.1. Presentation layer

The DSS derived from this architecture can be accessed through multiple channels, including data collection applications like Open Data Kit and Enketo, web applications, and mobile applications, providing a versatile platform for users.

Specifically, the data collection application, designed primarily for experts, features a "Beneficiaries Registration" module. This module streamlines the collection of participant information during technology dissemination events, such as field days and FFS. It allows researchers and extension agents to gather essential data for participant tracking and technology adoption monitoring, aligning with user-centered design principles for intuitive and user-friendly interfaces.

The web and mobile applications provide access to the three main modules of the DSS. The first module, "IPM Technologies Options", serves as a knowledge repository encompassing information on insects, their natural predators, general advice, and expert recommendations for pest control while preserving the ecosystem. It also provides personalized IPM technology recommendations tailored to the user's local agroecological context. The second module, "Conversations", fosters a community of practice by enabling users to engage in discussions and share images related to insect issues, creating a collaborative environment. The third module, "Observations", caters exclusively to experts, permitting them to record, store, and analyze data concerning unusual pest or crop-related events. To ensure seamless operation, the architecture includes a local database, ensuring system functionalities even during unstable internet connectivity. Additionally, a service worker component is integrated, facilitating resource caching, offline access, and efficient communication with the application layer.

It is also worth noting that although designed for developing countries, the software architecture and its modules remain coherent within a global context insofar as many of the challenges they address are still relevant in developed countries (Marinko et al., 2023).

6.2. Application layer

The application layer serves as the backbone of the system, responsible for executing the core business logic. Within this layer, three distinct engines operate, each dedicated to addressing specific limitations identified earlier: the agroecology engine, the triangulation engine, and the mapping engine.

6.2.1. Agroecology engine

The primary aim of this engine is to furnish the "IPM Technologies Options" module with a tailored list of IPM technologies, aligning them with the specific agroecological characteristics of the user's location. To achieve this, the engine employs a two-step approach. Initially, an agroecological classification algorithm is applied, utilizing a broad spectrum of biophysical and socioeconomic variables, including climate, topography, soils, water resources, and demographic factors, all of which are determined by the field's geographic coordinates (Egbebiyi et al., 2019; Kombat et al., 2021). Subsequently, a second algorithm utilizes the results of this classification, combined with information about the targeted pest. This information triggers two distinct queries within the database. The first query retrieves IPM technologies compatible with the pest, while the second identifies those matching the field's agroecological class. By applying predefined criteria such as effectiveness, availability, cost, and sustainability, the engine synthesizes the outcomes of these two queries, producing a list of the most suitable IPM technologies for pest control specifically tailored to the local agroecological context.

Two prominent challenges can be addressed to significantly enhance the efficiency of this engine. The first challenge involves the development of a dissimilarity index, connecting sites with analogous characteristics and climates across both space and time. To tackle this first challenge, advanced machine learning algorithms and statistical techniques can be employed to scrutinize and model the relationships between diverse agroecological variables, such as soil type, climate, and topography. These models can then be utilized to construct the dissimilarity index. The integration of this index would augment the recommendation system's precision and adaptability to evolving agroecological conditions. It would no longer rely solely on static database information but instead continuously evolve in response to current and future agroecological trends. A potential approach to achieving this is illustrated in Ramirez-Villegas et al. (2011), wherein a dissimilarity index is introduced to characterize agroecological similarity between two sites using the weighted Euclidean distance.

To further enhance the effectiveness of the IPM recommendation module, a second challenge could involve the development of a "Social Impact Engine". This engine would take into account critical socioeconomic factors, including the crop's local importance, population density, average income, and the costs associated with implementing a specific IPM technology. Integrating this proposed engine with the agroecology engine would create a more comprehensive and robust system that assesses the environmental and social impacts of adopting IPM technology holistically. This integration would enable the identification of the most suitable approach for a particular crop, considering variables like market demand, economic viability, labor availability, and local cultural practices. A pertinent example highlighting the importance of incorporating socioeconomic elements can be found in Liu et al. (2017). Their study demonstrates that synergizing the DSS with the socioeconomic context can result in improved pest management outcomes, increased net returns, and reduced risks associated with the implementation of IPM technologies.

6.2.2. Triangulation engine

The triangulation engine aims to improve the user experience in the "Conversations" module by integrating a feature to locate nearby users. This functionality could serve various purposes, including connecting farmers for networking and collaboration or identifying potential buyers or suppliers for agricultural products. This engine can significantly contribute to facilitating knowledge sharing on biological and cultural control technologies. Indeed, users who are geographically close to each other are more likely to belong to the same agroecological zone and share similar pest management recommendations. By leveraging this proximity-based approach, the engine could facilitate knowledge sharing and collaboration between neighboring users, allowing them to exchange feedback and share knowledge gained during and after the deployment of recommended technologies.

In its operation, this engine would take inputs such as the geographical coordinates of a farmer's address, the geographical coordinates of their field, and two specified radii. Initially, it would classify the farmer's field agroecologically, employing an algorithm similar to the "Agroecology engine". Subsequently, using the first radius as input, the engine would identify all fields near the farmer's field with the same agroecological classification. It would then determine the list of users associated with these neighboring fields using another algorithm. The engine would retrieve the geographical coordinates of these users' addresses and employ the second input radius to identify users located close to the farmer, ultimately providing a list of nearby users as the final result.

One potential enhancement to improve the efficiency of this engine and the "Conversations" module is to incorporate Natural Language Processing and convolutional neural network techniques to introduce an innovative chatbot. This chatbot could identify pests or diagnose crop issues from user-provided images and interact with the agroecology engine to suggest suitable IPM technologies. It could also collaborate with the triangulation engine to propose potential users for networking or collaboration based on their proximity to the farmer's location. This would enrich the "Conversations" module by offering an innovative approach to connect users with similar agroecological conditions and interests, potentially boosting the adoption and implementation of IPM technologies. A relevant example of a similar approach can be seen in the *Plantix mobile app,*[9] which uses image recognition technology to diagnose plant diseases and provide recommendations for farmers, effectively using chatbot functionality and IPM technologies for improved outcomes.

An additional intriguing challenge could involve designing an early-warning module by combining the capabilities of the triangulation engine with the "Conversations" module. The triangulation engine could retrieve observations from FFS in a specific region and utilize predictive algorithms to anticipate potential issues for farmers in that region, such as pest infestations or adverse weather conditions. This integration would empower the DSS to provide farmers with early warnings about potential problems and proactive recommendations.

6.2.3. Mapping engine

The Mapping engine primarily supports the "Observations" module by providing an interactive map for visualizing expert records. It can also filter observations based on criteria like country, crop, or pest and allow users to download them in various formats. The engine takes inputs from the "Observations" module's filtering criteria and retrieves relevant observations and their geographic coordinates via a database query. These observations are then passed to a "Mapping Application Programming Interface (API)" for rendering, providing an interactive map of the filtered observations as output. An example of a similar approach can be found in the iNaturalist app (Nugent, 2018), which integrates mapping features to visually display user-contributed wildlife observations, enabling seamless exploration and analysis of species distribution.

A significant challenge of this engine could be the scalability issue. As the number of observations increases, the processing time for retrieving and rendering the data may increase exponentially, leading to a slow response time and a poor user experience. Strategies like caching, indexing, and load balancing can be used to optimize database queries and reduce processing times.

Beneath the three engines, a "Datasync and Replication Engine" is also present in the architecture, providing data synchronization and replication services between the different layers. This engine ensures data consistency by performing regular communications between the local database of the presentation layer, the application layer's engines, and the persistence layer's databases. It is a critical component in maintaining the integrity and reliability of the system's data, ensuring its availability even in the absence of an Internet connection.

6.3. Persistence layer

The persistence layer of the architecture incorporates two storage systems. The first is a relational database connected to the data collection application, primarily used during technology dissemination events to record beneficiary data like names, contacts, addresses, fields, and trained IPM technologies. The second is a NoSQL database utilized by the web and mobile applications through the three engines of the application layer. This database contains user lists with roles (experts, extension agents, farmers), expert-issued observations, and a categorized list of IPM technologies based on agroecological classifications, which forms the core of the recommendation system.

Consequently, the loading process of the IPM technologies table involves experts performing, in the first step, an agroecological classification of different zones according to biophysical and socio-economic variables; then, in the second step, a mapping between a list of IPM technologies and the different agroecological classes obtained. The last component of the persistence layer is an API in charge of data synchronization between the two databases to prevent duplication and maintain consistency. It also ensures that the NoSQL database will have a consistent global view of the beneficiaries' data.

The persistence layer of the architecture could be further enhanced by developing or adopting an ontology to represent the knowledge domain of IPM technologies formally. By explicitly modeling the concepts, relationships, and rules relevant to IPM, an ontology can provide a more structured and efficient way to store and retrieve information, improving the accuracy and consistency of the data used by the DSS. Furthermore, adopting a common ontology can facilitate interoperability between different IPM DSS, allowing for easier sharing and exchange of information, reducing redundancy, and improving the overall effectiveness of IPM dissemination efforts. As an illustrative instance, there is the IPM ontology developed by Phoksawat et al. (2019) that can be used to guide the development of intercropping applications in rubber plantations, as outlined in Section 4. It is also worth noting that the two storage systems must also include robust data encryption and access controls to ensure the confidentiality and ownership of the data provided by the farmers, thereby ensuring privacy and security.

7. Conclusion

Promoting the adoption of Integrated Pest Management (IPM) technologies in developing countries poses a considerable challenge for the scientific community. To address this, innovative dissemination tools with enhanced features are essential to facilitate learning and uptake of these technologies. Based on a review of approximately 32 biological and cultural control technology dissemination tools, this study highlights five key limitations hindering regular use by farmers. These limitations include accessibility, user feedback, knowledge sharing, and the criteria for recommending IPM technologies. To overcome these challenges and improve the user experience, a user-centered design approach is proposed in the form of a novel software architecture for Decision Support Systems tailored to farmers and experts. This architecture tackles accessibility issues by incorporating a local database for offline use, a mapping engine for user-friendly data visualization, and a data collection application for simplified user registration. It addresses user feedback and knowledge-sharing concerns through a conversation module paired with a triangulation engine to facilitate networking among DSS users. Moreover, it integrates an agroecology engine to enhance technology recommendations by considering the user's agroecological context.

By addressing these identified challenges and integrating the proposed modules and engines, this architecture is expected to significantly improve the dissemination of IPM technologies. Additionally, it lays the foundation for future research and development efforts aimed at creating a reference decision support system for IPM technology delivery based on the insights gained from this study.

CRediT authorship contribution statement

Franck B.N. Tonle: Conceptualization, Data curation, Methodology, Investigation, Validation, Writing – original draft, Writing – review & editing. **Saliou Niassy:** Project administration, Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. **Milliam M.Z. Ndadji:** Conceptualization, Data curation, Methodology, Supervision, Writing – original draft, . **Maurice T. Tchendji:** Supervision, Validation, Writing – original draft. **Armand Nzeukou:** Supervision, Validation, Writing – original draft. **Bester T. Mudereri:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Kennedy Senagi:** Conceptualization, Data curation, Methodology, Validation, Visualization, Writing – original draft. **Henri E.Z. Tonnang:** Project administration, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

[9] https://plantix.net/.

Table 3
Additional information on the digital dissemination tools reviewed.

Reference	Acronym/ Name	Category	Targeted continents	Chat features	Offline mode	Availability	Targeted pests/crops	Threshold/Modeling method used	Key modules	Recommendation's inputs data	Classification rationale
(a) Decision support system											
Elliott et al. (2004)	–	Biological control	North America	No	No	Proprietary	Cereal Aphids and greenbugs	Greenbugs/tiller	Economic threshold calculator, natural enemy identification	Insecticide costs, wheat yield loss, air temperature	The DSS has a *natural enemy identification* module that allows users to identify and assess the presence of natural predators and beneficial organisms to promote natural biocontrol.
Magarey et al. (2007)	NAPPFAST	Biological control	North America	No	No	Proprietary	*Phytophthora ramorum*, *Phakopsora pachyrhizi*, *Phragmidium violaceum*	Dynamic (changes depending on the pest)	Plant disease forecast, pest detection	Temperature, wind speed, evaporation, precipitation	*NAPPFAST* has a *biological templates* component that allows users to create models that can be used to create a pest risk map. It also has a natural enemy identification module.
Zhu et al. (2007)	GMDSSCM	Cultural control	Global	No	No	Proprietary	Wheat, rice, rape and cotton	Combination of four crop simulation models	Cultural control technologies recommendation, real-time growth simulator	Air temperature, rainfall, crop variety, soil type	*GMDSSCM* focuses on crop management practices by integrating process-based models for various crops (wheat, rice, rape, and cotton) to optimize crop growth and yield.
Jones et al. (2010)	WSU-DAS	Biological control	North America	No	No	Proprietary	Washington tree fruit pests (10 specific pests supported)	Dynamic (changes depending on the pest)	Pest population & status prediction, pesticide recommendation database	Temperature, precipitation, wind speed, atmospheric pressure	*WSU-DAS* incorporates environmental data, pest model predictions, identification of natural enemies, and management recommendations, emphasizing and promoting biocontrol strategies.
Antonopoulou et al. (2010)	MAFIC-DSS	Cultural control	Europe	Yes	Yes	Proprietary	Maize, soybean, sorghum, cardoon, and rapeseed	Rule-based modeling	Cultivation advisory, crop deficiencies identification, crop recommendation	Cultivation history, soil and climate characteristics, agricultural policy, market demands	*MAFIC-DSS* assists farmers in selecting appropriate alternative crops, providing information and support throughout the cultivation period, including cultivation, fertilization, and irrigation strategies.
Samietz et al. (2011)	SOPRA	Biological control	Europe	No	No	Proprietary	Orchard fruit pests	Dynamic (changes depending on the pest)	Pest population & status prediction, pesticides database	Solar radiation, air and soil temperature	*SOPRA* optimizes pest management timing by simulating pest populations' phenology based on local weather data, thus promoting biocontrol strategies for effective insect pest control.
Chauhan et al. (2013)	AQUAMAN	Cultural control	Australia	No	No	Proprietary	Peanuts (*Arachis hypogaea L.*)	APSIM simulator	Irrigation scheduler, water-use optimizer	Soil type, sowing date, crop variety, temperature, rainfall	*AQUAMAN* aids growers in scheduling irrigations by simulating irrigation timing and depth using a combination of FAO irrigation scheduling guidelines and APSIM modeling framework.
Rossi et al. (2014)	vite.net®	Cultural control	Europe	No	No	Proprietary	Grapes	Combination of several crop and disease simulation models	Real-time vineyard monitoring, IPM technologies recommendation	Air temperature, relative humidity, leaf wetness, rainfall	*Vite.net®* targets vineyard managers by offering real-time monitoring of vineyard components coupled with advanced modeling, yielding tailored alerts, and cultural control strategies.
Backoulou et al. (2014)	–	Biological control	North America	No	No	Proprietary	Panicle Caterpillars	Larvae/panicle	Economic threshold calculator, pest identification	Plant density, plant stage, grain value, insecticide costs	The DSS has a *natural enemy identification* module that allows users to identify and assess the presence of natural predators and beneficial organisms to promote natural biocontrol.
Small et al. (2015)	BlightPro DSS	Biological control	North America	No	Yes	Proprietary	Late blight fungus (*Phytophthora infestans*)	Blight units/day and fungicide units/day	Plant disease forecast, fungicide application scheduler	Temperature, relative humidity, precipitation, wind speed	*BlightPro* provides location-specific recommendations based on weather data and validated disease models, contributing to optimized biocontrol agent use.
del Águila et al. (2015)	Web-Pest	Biological control	Europe	No	No	Proprietary	Tomato and grape pests (20+ specific pests supported)	Dynamic (changes depending on the pest)	Action threshold calculator, Biocontrol technologies recommendation	Sampling date, pathogen presence percentage, beneficial fauna status	*Web-Pest* streamlines biocontrol implementation by integrating rule-based techniques and standardized pest management processes to recommend appropriate biocontrol agents.
Todorovic et al. (2016)	HT-DSS	Cultural control	Europe	No	No	Proprietary	Generic (10 crops supported)	Combination of crop growth simulation models	Irrigation scheduler, water-use optimizer	Temperature, daily rainfall, relative humidity	*HT-DSS* aids growers in scheduling irrigations by simulating irrigation timing and depth using FAO-56 approach to estimate the reference crop evapotranspiration.
Giles et al. (2017)	myFields	Biological control	North America	No	No	Open-source	Greenbugs and soybeans aphid	Greenbugs/tiller	Economic threshold calculator, pest scouting helper, IPM technologies warehouse	Control cost, market value, season	*myFields* integrates pest and natural enemy data aggregation for effective sampling, varietal development and deployment, and site-specific real-time management guidance for effective biocontrol.
Cañadas et al. (2017)	SAVIA	Biological control	Europe	No	No	Proprietary	Table grape pests (20+ specific pests supported)	Dynamic (changes depending on the pest)	Pest risk estimator	Infestation state, phenological stage, environmental conditions	*SAVIA* employs a model-driven approach to provide decision support in the selection of appropriate biocontrol agents for the management of table grape pests.
Patel et al. (2018)	DOMIS	Cultural control	Asia	No	No	Proprietary	Generic (pulses, spices, ornamental crops)	Combination of crop simulation models	Irrigation scheduler, water-use optimizer	Field dimensions, water source, canopy factor, plant spacing	*DOMIS* helps farmers as well as policy makers and researchers to obtain optimal design and cost estimates of a micro-irrigation system.
Li et al. (2018)	WIDSSLI	Cultural control	Asia	No	No	Proprietary	Winter wheat and summer corn	Water balance modeling	Soil moisture monitoring, irrigation and water-use optimizer	Air temperature, relative humidity, precipitation, wind speed	*WIDSSLI* helps growers schedule irrigations using the FAO-56 dual crop coefficient approach to simulate the soil water balance of different layers.

(*continued on next page*)

Table 3 (*continued*).

Phoksawat et al. (2019)	–	Cultural control	Asia	No	No	Proprietary	Crops in rubber plantation	Ontology	Intercropping plants recommendation	Age of rubber tree, spacing between rows of rubber trees, water sources	The DSS provides an ontology to recommend intercropping plant recommendation based on the characteristics and condition of the farmer's area.
Yeow and Becker (2019)	JIS	Biological control	Global	No	No	Proprietary	Greenhouse whitefly (*Trialeurodes Vaporariorum*)	–	Pest population predictor	Initial pest population counts, daily maximum and minimum temperature	*JIS* aids greenhouse growers in efficiently maintaining pest populations below the ETL by simulating pest population projections.
Lagos-Ortiz et al. (2020)	AgriEnt	Cultural control	South America	No	No	Proprietary	Generic (6 crops supported)	Ontology	Crop treatment recommendation	Crop symptoms	*AgriEnt* supports farmers in crop management and treatment. Using ontologies and a rule-based inference engine, it diagnoses crops based on user-provided symptoms and recommends treatments.
Butts et al. (2020)	Irrigator Pro	Cultural control	North America	No	No	Proprietary	Peanuts, cotton, corn	Rule-based modeling	Soil moisture monitoring, irrigation, and water-use optimizer	Min and max soil temperature, rainfall, irrigation	*Irrigator Pro* helps growers schedule irrigations by integrating experiential knowledge, observed data, and field soil water potential measurements to optimize crop water management.
Simionesei et al. (2020)	IrrigaSys	Cultural control	Europe	No	Yes	Proprietary	Generic (6 crops supported)	MOHID-Land model (water balance modeling)	Soil moisture monitoring, irrigation, and water-use optimizer	Temperature, solar radiation, relative humidity, wind speed, rainfall	*IrrigaSys* helps growers schedule irrigations by computing the soil water balance based on weather data downloaded from the nearest meteorological station.
Pahmeyer et al. (2021)	Fruchtfolge	Cultural control	Europe	No	No	Open-source	Generic (100+ crops supported)	Mixed integer linear programming	Crop recommendation, cropping & manure allocation visualization	Soil type, soil quality, previous crop effects	*Fruchtfolge* helps farmers define cropping plans and fertilization strategies based on an optimization model that integrates location factors, policy restrictions, and market considerations.
Kessler et al. (2021)	–	Cultural control	Europe	No	No	Proprietary	Winter wheat	Ontology	Nitrogen Fertilization Management	Soil temperature, soil moisture, soil textures	The DSS has a *crop management module* supported by an ontology, delivering pertinent information and recommendations for nitrogen fertilization in winter wheat cultivation.
Rincon et al. (2023)	AGROSAVIA	Biological control	South America	No	No	Proprietary	Tomato leafminer (*Phthorimaea absoluta*)	Larvae/plant	Action threshold calculator, Dynamic sampling scheduler	Labor wage cost, insecticide cost, number of plants, age of the crop	*AGROSAVIA* integrates an action threshold module based on the pest life stage for optimizing biological control of the tomato leafminer.
(b) ICT learning platform											
Jansen (2013)	*IOBC-WPRS Database*	Biological control	Africa, Asia, Europe	No	No	Proprietary	Generic (25+ species supported)	–	Selective pesticide database	–	*IOBC-WPRS Database* promotes biological control by providing information (active ingredient, dose, duration) about several biocontrol agents and products.
Jørgensen et al. (2014)	*Eu-rowheat.org*[2]	Biological control	Europe	No	No	Proprietary	Generic (10+ pests supported)	National boundaries	Pest identification, pest alert, biocontrol measures recommendation	Targeted pests	Eurowheat.org promotes biological control by providing information about control thresholds, fungicide efficacy, fungicide resistance, and pathogen virulence for the management of winter wheat.
Tozer et al. (2017)	*AgPest*	Biological control	Australia	No	No	Proprietary	Generic (30+ pests supported)	National boundaries	Pest identification, pest alert, biocontrol measures recommendation	Targeted pests	*AgPest* has a *natural enemy identification* module that allows users to identify and assess the presence of natural predators and beneficial organisms to promote natural biocontrol.
Khan et al. (2018)	*icipe PUSH-PULL*[5]	Cultural control	Africa	No	No	Proprietary	Cereals (maize and sorghum)	–	Pathways, dissemination materials, videos, media	–	*icipe PUSH-PULL* promotes cultural control by providing training materials, learning videos, and publications about the components, functioning and deployment of the push-pull technology.
Otieno et al. (2020)	*Plantwise web*[1]	Biological control	Global	Yes	Yes	Proprietary	Generic (300+ pests supported)	National boundaries	Biocontrol technologies recommendation, eLearning, knowledge bank	Country, user occupation, crop, pest	*Plantwise web* promotes biological control by providing a knowledge bank, recommendations, and learning resources pertaining to IPM biocontrol technologies.
Bentley et al. (2022)	*Access Agriculture*[6]	Cultural control	Africa, Asia, Australia, South America	No	No	Proprietary	Generic (40+ crops supported)	–	Videos	Targeted crops	*Access Agriculture* promotes cultural control by providing learning videos and training materials on various sustainable farming practices and techniques using ecological approaches.
–	*COLEAD Training*[3]	Biological control	Global	Yes	Yes	Proprietary	Generic (20+ pests supported)	–	eLearning, pest identification	–	*COLEAD Training* promotes biological control by providing learning videos and training materials pertaining to IPM biocontrol technologies.
(c) Visual materials											
Leung et al. (2020)	*BINGO*[4]	Biological control	Europe	No	No	–	Spider mites	–	Videos	–	BINGO consists of two short educational videos about biological control aiming to educate teachers and growers about biocontrol and selective breeding concepts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix. DSS classification

A comprehensive table detailing the categorization of the tools used to generate the graphs presented in Section 5 is provided in this appendix. It is important to note that this categorization has been tailored to the scope of our study, which primarily focuses on Decision Support Systems (DSS) related to biological and cultural control methods. As a result, this classification should not be seen as overly restrictive; a DSS categorized as a "biological control tool" may include functionalities associated with other types of pest control (see Table 3). For example, WSU-DAS, classified as a "biocontrol tool", also incorporates a pesticide database, thus justifying its classification as a "chemical control" DSS (Jones et al., 2010).

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