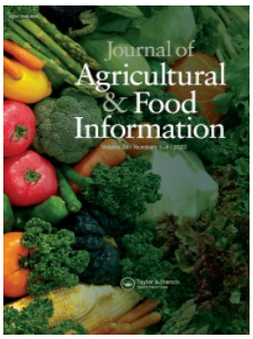

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A Review of CABI Digital Tools for Plant Health and Pest Risk Management

Hideo Ishii-Adajar[a], Katherine Cameron[b], Claire Palmer[b], Angel O. K. Li[b], Mariam A. T. J. Kadzamira[a], Sarah Fleming[b], Manju Thakur[c] and Adewale Ogunmodede[d]

[a]CABI UK Centre, Egham, UK; [b]CABI, Wallingford, UK; [c]CABI India, New Delhi, India; [d]Royal Agricultural University (RAU), Gloucestershire, UK

ABSTRACT

The contribution of CABI digital tools in enhancing plant health and pest risk management is examined. Six key digital tools are reviewed to draw themes on their benefits and challenges to users and assessed using the Principles for Digital Development as a guiding framework. CABI digital tools provide quick access to relevant information, support informed decision-making, and are open access and scalable. Enhancing user accessibility and considering diverse local contexts, especially in remote areas with poor internet connectivity, can extend their impact. Addressing financial and social sustainability, including gender barriers to mobile ownership, can also increase their contribution.

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Introduction

The advent of technology and the proliferation of digital platforms have ushered in innovative digital tools with transformative potential for agriculture and environmental management. These tools offer new opportunities for agricultural extension and advisory services, enhancing the accessibility of information and resources, particularly in remote areas and across various stakeholders (Amirova et al., 2020; FAO, 2021; Himesh et al., 2018). However, despite the emergence of digital tools, farmers still struggle to access information for effective management of plant pests and diseases, which pose major threats, especially to smallholder farmers in developing countries. These farmers often endure pest and disease infestation to crops which severely impact their household livelihoods, and at the same time, they grapple with making farm-level decisions based on limited and sometimes unreliable information

CONTACT Hideo Ishii-Adajar h.ishii-adajar@cabi.org CABI UK Centre, Bakeham Lane, Englefield Green, Egham, TW20 9TY, UK.

(Hoekman et al., 2005; Jarial & Sachan, 2021; Ristaino et al., 2021). This problem is exacerbated by increasingly understaffed extension systems and national plant protection organizations (NPPOs) that lack adequate resources to generate prompt and robust data for sending early warning alerts or providing timely advice for farmers (Adewopo et al., 2021; Kansiime et al., 2022). Thus, further development is needed for digital tools in agriculture to deliver solutions that bridge the information gap for smallholder farmers while also enabling advisory services to maximize the available resources of extension systems and NPPOs of developing countries (FAO, 2021). This paper seeks to highlight the contributions made in this area by CABI by reviewing the benefits, challenges and opportunities presented by its suite of digital tools as part of its broader aim to improve agricultural advisory services and, ultimately, farmer livelihoods.

CABI digital tools

CABI has developed a wide range of digital tools for improving plant health systems globally under the PlantwisePlus program Table 1. The PlantwisePlus program tackles challenges surrounding outbreaks of pests and diseases as well as poor awareness on the hazards of excessive pesticide use by "enhancing knowledge and uptake of integrated pest management (IPM) practices through responsive digital advisory tools" (CABI, 2024b). The program operates in 27 core countries and has a particular interest in six focus countries: Kenya, Uganda, Zambia, Ghana, Pakistan, and Bangladesh. The goal of PlantwisePlus is to help smallholder farmers improve food security and produce food more sustainably, but this objective is accomplished by supporting agricultural service providers who offer critical advisory services to farmers and act as important intermediaries. In other words, by improving the quality and timeliness of advice from agri-service providers, it is the farmers who ultimately benefit with better pest management, pesticide use, and overall crop health. Thus, the digital tools in Table 1 strategically address three areas of need for agricultural

Table 1. Overview of digital advisory tools developed by CABI.

Invasive species	Plant health and plant protection information	Digital learning products	Directory of digital advisory tools
CABI Compendium (Invasive Species Channel)	PlantwisePlus Knowledge Bank (PWKB)	Crop Pest Diagnosis Course	Crop App Index
Pest Risk Analysis (PRA) Tool	Fertilizer Optimizer Tool	Crop Pest Management Course	
Horizon Scanning Tool (HST)	PlantwisePlus Factsheet Library App	Introduction to BioProtection Products Course	
	BioProtection Portal (BPP)	Pest Diagnostic Simulator App	
	Crop Sprayer App		
	CABI Compendium (Crop Protection Channel)		

service providers (e.g. agro-input dealers, public and private extension officers, and plant doctors): (1) capacity strengthening, (2) access to reliable information, and (3) decision-making support.

Capacity strengthening tools such as CABI Academy and simulation games increase skills to carry out realistic tasks in a range of practice contexts that can be translated into the work environment. Tools providing access to reliable information include the PlantwisePlus Knowledge Bank (PWKB, upon which PlantwisePlus factsheets are published alongside a library of non-CABI pest management factsheets), CABI Compendium and the BioProtection Portal. These tools equip farmers and service providers with relevant and up-to-date information for different plant health threats, invasive species and registered biocontrol and biopesticide products, respectively. Decision-making support tools such as the Crop Sprayer App and Fertilizer Optimizer Tool facilitate faster and more accurate calculations for pesticide and fertilizer applications for farmers, while the Pest Risk Analysis Tool and Horizon Scanning Tool allow national plant protection organizations (NPPOs) to better prevent the spread of invasive species. Lastly, the Crop App Index compiles a comprehensive inventory of over one thousand digital tools to support decision-making in crop production and plant health, complementing CABI's own digital tool offering. Altogether, these digital tools and resources improve agricultural advisory services by strengthening the skills and knowledge of agri-service providers, thereby providing farmers more timely and accurate advice.

To guide good development practices for digital tools, CABI embraces the Principles for Digital Development (*Principles for Digital Development*, 2024). These nine principles offer best practices that help realize the full potential of information and communications technology (ICT) in international development, and the full list includes (1) understand the existing ecosystem, (2) share, reuse, and improve, (3) design with people, (4) design for inclusion, (5) build for sustainability, (6) establish people-first data practices, (7) create open and transparent practices, (8) anticipate and mitigate harms, and (9) use evidence to improve outcomes. By adhering to the Principles for Digital Development, CABI has clear guidance on the strategy and pathway of change for the implementation of digital advisory tools that enhance the knowledge and uptake of IPM practices, which consequently leads to safer, more sustainably produced food and improved farmer livelihoods.

Previous studies have conducted assessments of individual CABI digital tools that reveal important insights into their outcomes and impact (see Fleming and Thakur 2024; Kadzamira et al. 2022, 2023; Williams et al. 2021, 2022). This study aims to compile these insights and draw broad themes about the tools' benefits and challenges to evaluate the progress

of CABI's digitally supported development work. Altogether, this review offers a comprehensive source for understanding the CABI digital tools of the PlantwisePlus program as well as their role and impact in enhancing pest risk preparedness, pesticide use reduction, and plant health management.

Study approach

The guiding research questions for this review are as follows:

- What are the benefits in using CABI digital tools?
- What are the challenges for adopting and implementing CABI digital tools?
- What do the benefits and challenges say about the overall contribution of CABI digital tools in enhancing plant health and pest risk management?

The first two questions are answered through a thematic analysis of user feedback and insights from prior studies. More specifically, the thematic analysis collates study findings that report on individual digital tools and draws broad themes about their benefits and challenges. This approach is feasible because each of the tools provide expert scientific information in a digital format with the aim of improving a particular aspect of plant health or pest risk management. As a result, the studies included in the review generally report to what extent the tools are achieving these improvements as well as identify obstacles that hinder the tools from fully meeting users' needs. By compiling these individual study findings into broad themes, it is possible to then review the tools' benefits and challenges from a perspective that assesses the broader impact of the CABI digital tools, as articulated by the last question. This wider perspective is framed by the guidelines and practices outlined by the Principles for Digital Development (*Principles for Digital Development*, 2024).

The CABI digital tools included in this review are the Invasive Species Channel of the CABI Compendium (formerly the Invasive Species Compendium (ISC)), Pest Risk Analysis Tool (PRA), Horizon Scanning Tool (HST), BioProtection Portal (BPP), PlantwisePlus Knowledge Bank (PWKB), as well as digital learning products within CABI Academy such as the Crop Pest Diagnosis (CPD) and Crop Pest Management (CPM) courses. These tools are selected because previous assessments conducted user surveys and gathered analytics data that provide real insight into the users, benefits and challenges of each tool (Fleming & Thakur, 2024; Kadzamira et al., 2022, 2023; Williams et al., 2021, 2022). One exception is Williams et al. (2022) did not include a survey on the BioProtection Portal (BPP) but instead conducted a deeper analysis of search terms from

the analytics data to understand user engagement with the tool. More importantly, each tool targets a different aspect of plant health and pests for different users, thus allowing for a well-rounded assessment of the contribution of CABI digital advisory tools to managing plant health and assessing pest risk. Table 2 summarizes key details of these digital tools including their purposes, targeted audiences, platforms, and subscription costs.

Results

Benefits of CABI digital tools

The term "benefit" refers to the advantages or positive outcomes that are gained from using various digital tools in agriculture (Bronson & Knezevic, 2016). The most significant benefits from using CABI digital tools are providing quick access to relevant and reliable information as well as facilitating decision-making in identifying, assessing and managing plant pests and diseases, invasive species and other potential threats to plant health. Other benefits mentioned include open (free) access, market demand linkages and versatility of application (Fleming & Thakur, 2024; Kadzamira et al., 2022, 2023; Williams et al., 2021, 2022).

Quick access to relevant information

A major benefit of CABI digital tools is that they provide quick access to relevant information which results in substantial time and cost savings for users across diverse agricultural contexts. For instance, the ISC serves as a prime starting point for researchers globally and significantly reduces the time needed for initial information gathering. Respondents in a survey felt that it provides quick access to relevant information (17.6%), accurate and up-to-date information (13.4%) and presents this information in a useful format (12.5%) (Williams et al., 2021). The PRA Tool builds on the invasive species data to facilitate individual pest risk analyses, which involves assessing the probability of introduction, establishment and spread, as well as potential consequences. Informants in Ghana stated that the tool significantly reduces the time required for a PRA because it can generate thorough lists of pest species associated with specific commodities (Kadzamira et al., 2023).

Similarly, the HST excels in identifying and categorizing pests or invasive species linked to specific pathways of introduction in a country, state or province. 25% of respondents appreciated this capability to compile lists of pests in geographical areas. They felt that the HST provides quick access to relevant information (21%) and saves valuable time that would otherwise be spent navigating multiple websites for data (15%). Users also benefit

Table 2. Summary of CABI digital tools included in review.

CABI tool	Purpose	Target audience	Platform	Subscription	Assessment
CABI Compedium—Invasive Species Channel	Consolidates science-based information for global invasive species management by including detailed datasheets, a bibliographic database, full-text articles, images, and maps	• academic • policymakers • extension officers • weed specialist	Web based	None	Williams et al., 2021
BioProtection Portal (BPP)	Provides information on bioprotection products as well as links to product manufacturers and suppliers to enable the identification, sourcing, and application of the products for particular pest problems in a given country	• extension workers • farmers	Web based, mobile app	None	Williams et al., 2022
PlantwisePlus Knowledge Bank (PWKB)	Provides actionable plant health information as well as various tools for pest identification, crop management, and customized alerts. Includes diagnostic aids, species pages, and country-specific resources. Focuses on PlantwisePlus countries	• plant doctors • extension officers • agro-input dealers • agriculture students	Web based (and some core content in mobile app)	None	Kadzamira et al., 2022
Pest Risk Analysis (PRA) Tool	Utilizes scientific information from the CABI Compendium to serve as a decision-support framework for identifying, assessing, and mitigating plant pest-related risks as well as facilitating safe plant and product movement	• risk assessors • plant protection officers • quarantine officers • protected area managers • researchers	Web based	Gratis subscriptions for NPPOs in lower-income countries (raises revenues through subscriptions from higher-income countries)	Kadzamira et al., 2023
Horizon Scanning Tool (HST)	Utilizes scientific information from ISC to aid users in identifying and prioritizing invasive species threats	• risk assessors • plant protection officers • quarantine officers • protected area managers • researchers	Web based	Open access version (free) and premium version (subscription)	Kadzamira et al., 2023
Digital learning products (CABI Academy)	Provides global training, education and professional certification service through massive open online courses (MOOCs) such as Crop Pest Diagnosis (CPD) and Crop Pest Management (CPM). Courses are developed by subject matter experts, learning designers, and editorial staff at CABI	• teachers and trainers • extension officers • agro-input dealers • agriculture students	Web based	Gratis subscriptions in lower-income countries (raises revenues through subscriptions from higher-income countries)	Fleming and Thakur, 2024

Source: Author compilation from the literature.

from its accuracy and up-to-date information (13%) which enhances the quality of their research or project work (13%). Notably, stakeholders in Ghana find that the HST is more detailed than other available tools while stakeholders in Zambia highlight its rapid ability to identify priority pests (Kadzamira et al., 2023).

The PWKB plays a crucial role in fortifying defenses against plant pests and diseases by collating practical pest management advice from a wide range of organizations, including country-specific IPM decision guides developed by CABI in partnership with local experts (Cameron et al., 2016). Through regular updates from stakeholder collaboration, usability testing and market research, the platform adapts to evolving user needs, and respondents testify to this adaptation with 53% stating that the main reason they use the PWKB is that it provides quick access to information which they would otherwise need to search in a range of different sources, and nearly a third of respondents utilize its data to enhance their academic research (Kadzamira et al., 2022). The strong focus on locally relevant, actionable advice in the PWKB is also a core strength compared to other, more global and academic databases of IPM information. Through collaboration with local partners, the advice in the Factsheets for Farmers and Pest Management Decision Guides is verified for relevance and practicality in the local context alongside expert validation for scientific accuracy (Cameron et al., 2016).

The BPP presents objective information on bioprotection products to extension workers, agro-input dealers and farmers to support the identification, sourcing and application of biocontrol solutions for specific crop pest issues in a country. The value of engaging with this information is made evident through the fact that the most active user interactions are through product searches, search results and resources pages, especially for widely cultivated crops such as tomato, maize, mango and rice and their associated pests, and users reported that using the BPP increased their knowledge of biopesticides and biocontrol products (Williams et al., 2022). Lastly, with more time investment from the user, digital learning products such as the Crop Pest Diagnosis (CPD) and Crop Pest Management (CPM) courses offer well-organized, specific and relevant information about crop protection (Fleming & Thakur, 2024). In short, the digital tools consistently deliver to users accurate and up-to-date information that reduces their time spent on gathering relevant information and ultimately enhances productivity for managing plant health and pest risk.

Informed decision-making

Because CABI digital tools provide reliable, time-saving databases on plant pests and diseases, they help to inform decision-making for various stakeholders in agriculture. For example, the ISC is a go-to resource for

comprehensive information on invasive species that assists users with a wide range of tasks including developing pest information packages to support market access for fruit and vegetable exports, assessing risks related to importing live plants and seeds and conducting pest research including surveys, models, alerts, reports and surveillance plans (Williams et al., 2021). Similarly, the BPP is designed to overcome barriers in recommending and using biocontrol and biopesticide products by providing objective information on bioprotection products. This benefit is realized when a user engages with the BPP from a visit to a search result and then, more importantly, to a product view. Although the average conversion rate for the BPP from user visit to search result is 2.3%, just under the industry average of 2.5%, the conversion rate from search result to product view is almost 25%. Such a high conversion rate to view products based on a search result indicates that users are interested in receiving recommendations for available bioprotection products based on relevant searches (Williams et al., 2022). For the digital learning products, feedback from end-of-course questionnaires reveal that 82% of respondents felt that they are able to apply learning from the course to their current job roles, thus enabling them to further professional practice by actively implementing crop pest diagnosis and management methodology (Fleming & Thakur, 2024).

The PRA Tool and HST go a step further by strengthening the capacity of actors in national systems to manage and respond to invasive species. More specifically, the PRA Tool provides a framework and template that streamlines the process for recording risk management actions and communicating findings and recommendations to decision-makers and stakeholders. These immediate applications extend into supporting government policy actions across sectors, as was seen in a case involving infected tomatoes imported from Morocco to Ghana. The PRA report exposed weak links in government and policy systems and eventually contributed to better border protection in Ghana (Kadzamira et al., 2023). By aligning closely with international standards for phytosanitary measures (ISPM 11), the tool can continue to facilitate the integration of pest risk assessments into national policies. The survey found that respondents intended to utilize PRA results to implement or modify commodity import restriction and regulations, which subsequently influences trade flows between countries (Kadzamira et al., 2023). For the HST, the tool was developed to provide a quick and user-friendly means of categorizing and prioritizing potential invasive species that are not present in an area. The survey found that users utilize the HST results to engage in research (17.2%), gather information for surveillance (14.9%), conduct detailed pest risk analysis (12.6%), train and teach (12.6%), and collect information for rapid response and contingency planning (11.5%) (Kadzamira et al., 2023). The policy

actions from the PRA Tool and post-HST activities demonstrate that the combination of access to reliable information and support for decision-making provided by CABI digital tools can play a pivotal role in plant health and pest risk management.

Other benefits

The CABI digital tools have other intended benefits to users, the most notable of which is their open access feature. The ISC, BPP and PWKB are all free resources while the PRA Tool, HST and digital learning products have subscription features but maintain gratis subscriptions for lower-income countries. This open access seeks to ensure accessibility to a wide audience and maximize engagement with targeted groups. A more specific benefit of the BPP is that it facilitates market demand linkages by connecting users to product manufacturers and suppliers which increases availability of bioprotection products as well as raises awareness of alternative input solutions to chemical pesticides (Williams et al., 2022). The BPP also contains a development consortium that presents a strong example of collaboration between public-private partnerships which can contribute to financial sustainability of the portal itself while also broadening its stakeholder base and their buy-in. Finally, the PWKB is reported to demonstrate versatility in its applications, with over 20% turning to it for risk assessments, preparation of extension materials, writing proposals and policy development in addition to its main application of providing information to identify and manage plant pests and diseases (Kadzamira et al., 2022). Altogether, through open access to information, support for decision-making, market linkages, versatile applications and localized, practical advice, CABI digital tools offer benefits to users that contribute to plant health and pest risk management.

Challenges for CABI digital tools

Several challenges are identified for users trying to engage with CABI digital tools such as accessibility and awareness as well as different patterns of engagement across devices and regions. Another significant challenge is poor internet connectivity, particularly in the Global South, that acts as a major barrier to effectively utilizing the tools. Lastly, sustainability challenges that involve balancing the open access feature with costs of maintenance as well as local ownership are noted.

User awareness and accessibility

Understanding the extent to which users are aware of and can access CABI digital tools can help to shed light on the challenges that they face and on strategic improvements for addressing those challenges. For

example, many users of the CABI Compendium encounter the database through search engines, and users that are aware of the tool often run searches that use the species name and "CABI" for queries. This finding demonstrates the value of search engine optimization work conducted by CABI in 2019, but also led to comments by respondents for additional marketing and awareness raising (Williams et al., 2021). Even after discovering the Compendium, some users note difficulties in navigating the webpages and accessing relevant information, suggesting that there is room to enhance internal search capabilities for easier navigation. For the PWKB, most users find the website *via* search engines (78.2%) with very few users coming from social sites and/or pay-per-click advertising. However, an analysis of user flow journeys shows that a significant number of users leave the PWKB after landing on their starting page which is often a Technical Factsheet, a Factsheet for Farmers or a Pest Management Decision Guide. This drop-off trend raises questions about whether users were able to gather the information they needed from the PWKB (Kadzamira et al., 2023). Further feedback from users suggests that they are leaving the PWKB because they are able to get what they need as they have found the appropriate page by inputting relevant keywords into a generic search engine as opposed to browsing for it within the PWKB.

Accessibility can be limited by functionality such as in the case of the PRA tool where generated PRA reports may not match the reporting formats preferred by partners, raising potential issues in information exchange. Additionally, the tool is known to contain references to external databases that could be more accessible with embedded links (Kadzamira et al., 2023). However, the effective use of digital tools is also largely determined by the technical and language proficiency of users, sometimes serving as a barrier to widespread adoption. Many of the CABI digital tools require a certain level of technical expertise and English language proficiency which may explain why, for example, even though 117 NPPOs are eligible for gratis subscription, not all have adopted the PRA Tool (Kadzamira et al., 2023). Language proficiency is especially a problem for those in non-English speaking countries who would like to use digital learning products. Until now, the CPD and CPM courses have relied on imperfect translations through Google Translate and subject matter experts to reach audiences in Spanish, French, Kinyarwanda, Uzbek, Turkish, Arabic, and Bangla. While these translations have reduced barriers, some have indicated, namely Spanish speakers, that investments in full translations may be necessary (Fleming & Thakur, 2024). Thus, efforts to improve accessibility by addressing functionality issues and offering training initiatives for technical expertise and user support may help to overcome barriers to adoption and teach users to adapt the tools to institutional needs.

Engagement patterns across devices and regions

Differences in desktop and mobile usage patterns, revealed through user analytics data, highlight challenges faced by intended audiences of CABI digital tools. For instance, 77.3% of sessions that lasted over 60 seconds on the BPP originated from a desktop device, as compared to 2.7% from a tablet and 1.2% from a mobile device. This difference, although unsurprising because such information can be read on a desktop screen better than other devices, can pose a problem because the tool's target audience of farmers and agro-input dealers are more likely to rely on mobile devices (Williams et al., 2022). The tendency toward mobile usage is echoed by analytics data from the PWKB which show that the access device for users differs between the 27 core PlantwisePlus countries and non-PlantwisePlus countries. While the majority of users from PlantwisePlus countries access the PWKB *via* mobile devices—aligning with the popularity of mobile internet in developing regions—users from non-PlantwisePlus countries predominantly access the platform from desktop computers (Kadzamira et al., 2022). The predominance of mobile devices is also evident for digital learning products, where 58% of site visits to CABI Academy website is *via* mobile devices and the proportion of users completing courses on mobile devices ranged from 46% (Rwanda) to 74% (Bangladesh) (Fleming & Thakur, 2024). This variation underscores the importance of addressing mobile usability issues to make the tools more accessible, especially for intended users in areas where mobile devices are the primary means of internet access.

The need to make CABI digital tools more accessible for targeted users is further emphasized by different patterns of user engagement across geographic regions. Versatile tools such as the PWKB have regional differences in primary use and should maintain flexibility in varied user engagement. For instance, in Africa, the PWKB is primarily utilized for basic tasks such as identifying plant pests and diseases, while in North and South America, the platform is mainly used for research (Kadzamira et al., 2022). For the BPP, the analytics data show that the average conversion rate from user visits to search results hovers slightly below industry norms (Google Ads Helps, n.d.), but notable variation exists with countries such as Bangladesh, Kenya and Ghana which have relatively low conversion rates despite high overall visits. The low rates in these targeted countries call to attention the importance of not only attracting visitors to the portal but also enhancing user engagement and interaction within the portal (Williams et al., 2022).

For digital learning products, the nature of engagement requires users to be more active, such as signing up for an account or visiting multiple times to complete a course. Analytics data show that the average engagement time with learners of 40 min far exceeds the industry definition for

an engaged session of 10 seconds (Google Analytics, n.d.), and course completion rates for the CPD and CPM were 46.8% and 30.9%, respectively, between 2020 and 2021. However, the data also show that regional variation is evident because the engagement rate for Bangladesh, Rwanda, and Bolivia were 79%, 52%, and 51%, respectively. The higher engagement rate in Bangladesh is likely due to high enrollments that resulted from in-person promotion efforts such as orientation training which helped to increase the uptake of the courses especially amongst junior colleagues. In comparison, direct promotion efforts were not as prevalent in Rwanda, and few enrollments from Bolivia are likely due to language issues (Fleming & Thakur, 2024). Nevertheless, the high overall engagement rates with online courses suggest that users find value and motivation to continue visiting the course pages and completing the assessments. Despite the high engagement, key informants shared that having enough time for independent study is a barrier to course completion, and this can be especially true for extension workers who have very high workloads which can hinder continued professional development activities (Fleming & Thakur, 2024). Thus, digital learning tools must consider such barriers to translate high engagement rates into higher completion rates for digital learning tools.

Lastly, functional features within the tools that require regional specification can cause difficulties for users, as is the case for the HST. Users have raised concerns about inconsistency in including state subdivisions, forcing them to check several possible names to identify relevant regions. This additional step limits the effective searchability for geographic subdivisions in countries where engagement may already be hindered by digital and language proficiency (Kadzamira et al., 2023). Consequently, improvements to CABI digital tools should focus on facilitating easier and more effective searches that also include aligning to the capabilities of target audiences that tend to be mobile-reliant or have limited proficiency.

Broader challenges

A major challenge for the uptake of CABI digital tools is weak internet infrastructure, which can impact their effective utilization, especially for users in field sites across the Global South where the tools are often targeted. This is not a unique problem for CABI digital tools and is a challenge that all decision support tool providers face (Abate et al., 2023; Hackfort, 2021). Remote areas that have limited or intermittent connectivity have difficulty accessing online databases such as the ISC, BPP and PWKB as well as utilizing the functionality of tools like the PRA Tool and HST (Kadzamira et al., 2022, 2023; Williams et al., 2021, 2022). The impact extends beyond just inconvenience, as it impedes the timely and efficient

management of plant health and pest risks, limiting the tools' effectiveness in crucial areas. Recognizing this challenge, digital learning products such as CPD and CPM, PlantwisePlus factsheet app (including a subset of the PWKB content) and BPP app have promoted offline capabilities that allow users to download sections of the course or country-packs of content when internet access is available and then use them offline in the field (Fleming & Thakur, 2024). Although developing internet infrastructure might reach beyond CABI's sphere of influence, innovative solutions such as enabling offline capabilities and strengthening mobile accessibility within the CABI digital tools can still help to overcome the barrier of limited internet access. Working with the available resources and capacity of the users will ensure that CABI digital tools can serve their intended purposes for their targeted audiences across diverse contexts.

The final major challenge for CABI digital tools is establishing their sustainability, especially for tools that must maintain the balance between open access and financial viability. More specifically, the ISC, BPP and PWKB face sustainability issues due to the costs associated with maintaining and updating their data. These tools must secure long-term financial support not only for continued operation but also for constant improvements to user awareness, accessibility and functionality (Kadzamira et al., 2022; Williams et al., 2021, 2022). Without such support, researchers, extension officers and agro-input dealers, particularly in the Global South, will not have the means to retrieve essential data for their field work and other plant health- and pest risk-related tasks. The PRA Tool has set up a business model such that higher-income countries pay subscription fees that raise revenues to grant lower-income countries with gratis subscriptions, and the HST offers an open access (free) plan as well as premium (subscription) plan that includes access to the CABI Compendium (Kadzamira et al., 2023). These arrangements allow the tools to remain open access to intended users who may not have the financial means for a subscription, while also keeping the tools self-sufficient. Another aspect of sustainability that must be considered is local ownership. Ensuring that people continue to build skills and capacity through digital tools requires working creatively with local partners and institutions to promote and use the tools beyond the project lifetime support from CABI. Such efforts may include obtaining sponsorship by private sector actors, creating spin-off products to generate revenue, or even securing government funding for access for an entire country. Therefore, future planning for CABI digital tools should consider developing a strategy that transitions the tool from dependency on financial donors and CABI support to financial sustainability and local ownership so that the intended users in the Global South can rely on having long-term access to the tools.

Discussion

After comprehensively reviewing the benefits and challenges of CABI digital tools, it is important to put the broader impact of the tools into perspective. Using the Principles for Digital Development as a guiding framework, this discussion examines whether the tools fulfill the PlantwisePlus impact pathway of improving farmer advisory services that encourage the knowledge and uptake of IPM practices. In doing so, it is possible to determine the contribution of CABI digital tools as well as identify opportunities to further enhance plant health and pest risk management for smallholder farmers.

The greatest strength of CABI digital tools is that they use evidence to improve outcomes (Principle 9) for plant health and pest risk management. CABI has harnessed its extensive scientific knowledge on invasive species, plant health and pest risks to ensure that quality information is readily available to users. Users consistently found the digital tools to provide quick access to relevant information, resulting in substantial time and cost savings. More specifically, users stated that the tools significantly reduced the time needed for initial information gathering which ultimately enhanced their productivity. Having reliable access to information meant that users could make informed decisions more quickly for managing invasive species and other threats to plant health. The gathered information was also applied to a wide range of activities such as surveillance, research, training, contingency planning and more. And through tools that directly support decision-making, including the PRA Tool and HST, national actors were even able to address policy gaps, as was seen in the case of imported infected tomatoes for Ghana (Kadzamira et al., 2023). Although digital learning products such as the CPD and CPM require more time investment from the user, they offer specific and relevant information on crop protection that can be directly applied to current job roles or to advance professional practices (Fleming & Thakur, 2024). These results show that CABI digital tools are fulfilling the principle of using evidence to improve outcomes because quality information is available to the right people when they need it, and they use it to take action.

Despite the strength of being evidence-driven, CABI digital tools are noted to have limitations in their user-friendliness, suggesting that more can be done to incorporate the intended users in designing the tools (Principle 3). Key challenges that users faced include limited awareness of the tools as well as difficulties in navigating webpages and accessing information. The reasons for limited awareness were not fully uncovered in the studies, but the finding that most users come across the tools through search engines demonstrates the critical nature of search engine optimization work that was previously carried out as well as highlights

the potential for additional marketing or awareness raising (Kadzamira et al., 2023; Williams et al., 2021). Accessibility issues were attributed to insufficient technical, digital and language proficiency which demonstrates how further conversation with users is needed to understand their skillsets, needs and challenges. To this end, Kadzamira et al. (2022) proposes a set of recommendations for the PWKB largely focused on improving the delivery, type, and accessibility of technical content. First, diversifying information-sharing methods, including video and audio platforms, can enhance the learning experience and facilitate easy sharing of information. Second, augmenting visual and interactive aspects with updated pest information and more visualization of plant health problems can improve user engagement and experience. Third, increasing content in local languages, enhancing site navigation, and continuing to ensure free access can contribute to inclusivity.

While incorporating these recommendations alone would make the data more presentable and actionable for users (contributing to Principle 9), CABI is going a step further and engaging users in the improvement process to make changes iteratively so that the tools effectively meet user needs. This engagement takes place through a combination of user engagement workshops, observation of users interacting with the tools during their work activities (i.e. user shadowing), and feedback surveys. Iterative developments are piloted with users to gain insight into the benefits of any changes before being fully implemented. For example, workshops and shadowing sessions have recently taken place to collect user requirements for new AI-based functionality within CABI's digital tools (King, 2025) and for iterative improvements of PlantwisePlus digital tools more generally (Manjari, 2024). Such co-creation ensures that CABI digital tools are designed with the users, not for them, and will ultimately better address the specific characteristics and challenges of the people using the technology.

To bolster the efforts of designing CABI digital tools with users, a deeper understanding of the existing digital ecosystems for the tools should be developed (Principle 1). Digital ecosystems affect an individual's ability to access and use technology and are defined by factors such as culture, gender, and social norms, as well as political environment, economy, and technology infrastructure (*Principles for Digital Development*, 2024). For example, a commonly cited challenge for many digital tools is that weak internet infrastructure hampers their effective utilization, especially in remote field sites across the Global South (Hackfort, 2021; Porciello et al., 2022). Unreliable internet connectivity is not only inconvenient but can also impede the timely and efficient management of plant health and pest risks. This problem is exacerbated by the fact that the target audiences of many tools are extension officers, agro-input dealers and farmers, many

of whom access the tools through mobile devices which are dependent on remote internet connection (Porciello et al., 2022). Even the majority of users for the digital learning products access online courses on mobile devices (Fleming & Thakur, 2024). While the challenge of weak infrastructure is often outside of CABI's sphere of influence, dedicating time and resources to analyze their relevance in a digital ecosystem helps in developing innovative solutions. A strong instance of such innovation is enabling offline capabilities for the BPP and digital learning products which allows users to engage with the tools even without internet connection (Fleming & Thakur, 2024; Williams et al., 2022). By designing the tools with input from intended users and gaining a deeper understanding of digital ecosystems, further innovations will extend the impact of CABI digital tools on plant health and pest risk management.

The published information on tools such as the PWKB, CABI Compendium, and digital learning products are supported by extensive scientific literature while the technical design of the tools allow for open access, and these features ensure that the information sources and practices maintain a level of quality and transparency that give users trust and confidence. CABI's digital tools include information within the user interface about their sources of information and verification processes, reports are regularly published documenting how tools and content have been compiled and used (e.g. Cameron et al., 2016; Fleming & Thakur, 2024; Kadzamira et al., 2022, 2023; Williams et al., 2021, 2022), and feedback loops are provided for users, all of which supports the principle of creating open and transparent practices (Principle 7).

Another important feature of the CABI digital tools is the open access to its scientific expertise on plant health and pests. This benefit is vital for users because it seeks to ensure accessibility to a wide audience and maximize engagement. Even if the tools are not fully open access, there is gratis subscription for lower-income countries, as is the case for the PRA Tool and HST (Kadzamira et al., 2023). CABI grants gratis subscription because it recognizes that these decision-making tools offer invaluable information to lower-income countries that often do not have the resources to afford such technology. This practice not only maintains transparency with its intentions but also adheres to the principle of design for inclusion (Principle 4) by demonstrating that digital tools should overcome, not exacerbate, existing inequality.

Although the subscription structure of some digital tools has sought to include lower-income countries, CABI can drive further social progress by dismantling systemic barriers through its digital tools. One very significant barrier is the gender gap in mobile ownership which remains because women are less likely than men to use mobile internet, and they

tend to use it across a narrower range of activities. The factors for why women use mobile internet less than men are complex, but in low and lower-middle income countries, they are often attributed to affordability, literacy, digital skills and lack of perceived relevance (Jeffrie, 2023). Overcoming this barrier may require more direct engagement with women to ensure that they are also learning how to maximize the purpose of the digital tools, such as through marketing campaigns. The positive effects of marketing campaigns for CABI digital tools have already been demonstrated. For example, analytics data reveal that engagement with digital learning products was higher in Bangladesh as compared to Rwanda and Bolivia, likely due to in-person promotion efforts such as orientation training which helped to increase the uptake of the courses especially amongst junior colleagues (Fleming & Thakur, 2024). Even mass marketing campaigns that promote general information about integrated pest management (IPM) across multiple channels in local languages have been significantly associated with improved farmer knowledge of pesticide risks and safety precautions, as was seen in Rwanda and Uganda (Tambo et al., 2023). If these marketing efforts can be more strongly tailored to target women and address the factors that limit women from engaging with mobile internet, then the impact of the CABI digital tools on plant health and pest risk management can be extended due to the increased engagement.

Looking ahead, CABI should consider several important challenges and opportunities for its digital tools. First, building the tools for sustainability is essential to maximize long-term impact (Principle 5). Given that the tools are open access and currently depend largely on donor funding for upgrades and data maintenance, a loss of funding could result in interruptions that reduce the impact and reliability of the tools for stakeholders. The sustainability of the digital tools also depends on the social context such as gender norms or the extent of support from local partners. Therefore, CABI should not only ensure the design of the tools fit the daily workflows of users, but also develop a business model of self-sufficiency, and invest and collaborate with local stakeholders to build a long-term plan beyond project lifetime. It should be noted that, under the PlantwisePlus program, CABI has designed the digital tools for scale, and this intention is made evident by the fact that the program "aims to reach 75 million smallholder farmers in 27 countries, providing them with access to knowledge and skills they need to improve their production practices" (CABI, 2024b). The program has also launched several campaigns to market and train the digital tools to extension officers and agro-input dealers in these countries (CABI, 2024a). As such, CABI has moved beyond the pilot stages and enabled the tools to expand into new markets and regions that need more information and advice on invasive species and

plant health. Nevertheless, whether it is handing over to local entities or receiving sponsorship to continue providing the service, significant effort must be given to formulate sustainability models for these digital tools that will shape the strategy of CABI's engagement with donors, local partners, stakeholders and private sector entities.

Second, as CABI digital tools continue to expand in users and usage, there will also be opportunities to gather increasing quantities of analytics data. While user analytics data are important for donor reporting and usage insights, it is critical to establish people-first data practices (Principle 6) which includes anticipating and mitigating harms (Principle 8) from access to private data. Establishing responsible practices and transparency with how personal and sensitive information is acquired, used, stored and shared across all tools will be a crucial part of keeping the best interests of users and institutions.

Third, if users signal that additional functionality is required, CABI can consider sharing, reusing and improving existing products and approaches (Principle 2). CABI's Crop App Index already collects a database of externally developed tools that serve similar purposes, so modifying or adapting elements of these existing tools or even engaging with their owners through partnerships is another way to further improve and co-create the overall quality, applicability and impact of CABI digital tools. Such engagement is at the heart of many of the CABI tools and their content—for example, the factsheets that are developed as part of collaboration with local partners. To encourage collaboration, CABI has started to share its insights and strategies across the development sector (CABI, 2024a) with the idea that a collaborative effort from the global development community that brings together resources and expertise in plant health and pest risk management will accomplish more than the organization can on its own. Another example is the BPP which encourages public-private partnerships within a development consortium. Although it requires time, planning and dedication, being collaborative ensures that all the principles of digital development are put into practice and opportunities are opened to strengthen the global community as it tackles the current-day challenge of increasing food security and improving farmer livelihoods.

Conclusion

This study explores the contribution of CABI digital tools in enhancing plant health and pest risk management as part of the PlantwisePlus program that promotes the knowledge and uptake of IPM practices for smallholder farmers. Previous assessments are reviewed to find common themes of benefits and challenges for six key CABI digital tools: the Invasive Species Channel (ISC) of the CABI Compendium, Pest Risk Analysis

(PRA) Tool, Horizon Scanning Tool (HST), BioProtection Portal (BPP), PlantwisePlus Knowledge Bank (PWKB), as well as digital learning products within CABI Academy such as the Crop Pest Diagnosis (CPD) and Crop Pest Management (CPM) courses. These benefits and challenges are then examined within the framework provided by the Principles for Digital Development which seek to realize the full potential of ICT in international development projects. The findings reveal that CABI digital tools excel in providing quick access to relevant information for extension officers, agro-input dealers, NPPOs and farmers, and helps them to make informed decisions for managing threats to plant health. However, the impact of the tools can be extended by co-designing with users as well as better understanding the variety of digital ecosystems in which the tools are applied, especially remote areas across the Global South that have poor internet infrastructure. On the other hand, CABI digital tools are open access and maintain transparent practices supported by extensive scientific knowledge, and this provides trust and confidence to users seeking farmer advisory services that promote knowledge and uptake of IPM services. Building on this strength, CABI should leverage its digital tools to overcome social barriers, such as the gender gap in mobile internet, by campaigning and targeting for more engagement from women.

Going forward, CABI should consider the importance of ensuring the financial and social sustainability of the tools, establishing people-first data practices which includes anticipating and mitigating harms related to data privacy, as well as sharing, reusing and improving on other digital tools with similar purposes. As work progresses in these areas, the Principles for Digital Development should continue to guide organizational decisions that maximize the agency of people and communities in building their capacity to manage pest risks and plant health. As an initial step, this study has utilized the principles to qualitatively assess broad themes about the benefits and challenges of CABI digital tools, but subsequent steps will entail defining how the principles can be operationalized within the work and sphere of influence of the PlantwisePlus program. Such steps can involve regular monitoring and evaluation of the tools through analytics data as well as mixed methods surveys of local users and relevant stakeholders. Altogether, CABI has made strong contributions to enhancing plant health and pest risk management with its digital tools, and there are opportunities to further this work that will result in safer, more sustainably produced food and, ultimately, improved farmer livelihoods.

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ORCID

Hideo Ishii-Adajar http://orcid.org/0000-0001-6611-7285
Katherine Cameron http://orcid.org/0000-0001-5344-2521
Claire Palmer http://orcid.org/0000-0002-3997-3972
Angel O. K. Li http://orcid.org/0009-0000-9789-9101
Mariam A. T. J. Kadzamira http://orcid.org/0000-0003-3652-508X
Adewale Ogunmodede http://orcid.org/0000-0001-6388-2870

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