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Contrasting National Plant Protection Needs, Perceptions and Techno-Scientific Capabilities in the Asia-Pacific Region

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Pests and pathogens inflict considerable losses in global agri-food production and regularly trigger the (indiscriminate) use of synthetic pesticides. In the Asia-Pacific, endemic and invasive organisms compromise crop yields, degrade farm profitability and cause undesirable social-environmental impacts. In this study, we systematically assess the thematic foci, coherence and inclusiveness of plant protection programs of 11 Asia-Pacific countries. Among 23 economically important diseases and 55 pests, survey respondents identified rice blast, rice brown planthopper, citrus greening disease, Tephritid fruit flies and fall armyworm as threats of regional allure. These organisms are thought to lower crop yields by 20–35% and cause management expenditures up to US$2,250 per hectare and year. Though decision-makers are familiar with integrated pest management (IPM), national programs are invariably skewed toward curative pesticide-intensive control. Pesticide reductions up to 50–100% are felt to be feasible and potentially can be attained through full-fledged IPM campaigns and amended policies. To rationalize farmers' pesticide use, decision criteria (e.g., economic thresholds) wait to be defined for multiple crop x pest systems and (participatory) training needs to be conducted e.g., on (pest, disease) symptom recognition or field-level scouting. Efforts are equally needed to amend stakeholder perceptions on ecologically based measures e.g., biological control. Given that several Asia–Pacific countries possess robust techno-scientific capacities in various IPM domains (e.g., taxonomy, molecular diagnostics, socioeconomics), they can take on an active role in regionally coordinated campaigns. As such, one can reinvigorate IPM and ensure that preventative, non-chemical pest management ultimately becomes the norm instead of the exception throughout the Asia–Pacific.

Keywords: plant health, invasive species management and control plans, integrated pest management (IPM), crop protection policy, farmer knowledge, agroecology

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INTRODUCTION

Plant diseases and animal pests jeopardize global agricultural production and compromise food security, human nutrition, economic prosperity and farmer livelihoods. In the absence of control measures, these biotic constraints lower crop yields by a respective 16–18% globally (Oerke, 2006) while their impacts are routinely of transboundary nature i.e., unconfined by national borders. Pests such as locusts or noctuid moths actively disperse within and between continents (Johnson, 1987; Showler, 2019) while wind patterns distribute pathogens on a global scale (Brown and Hovmøller, 2002). For major food crops such as wheat, rice or maize, pests and pathogens thus inflict combined losses of 21.5–30.0% (Savary et al., 2019), with impacts often exacerbated in food-deficit regions or for (re-)emerging constraints, and increasingly linked to climate change (Bebber, 2015; Chaloner et al., 2021).

In the Asia-Pacific region, transboundary pests and pathogens (TPPs) cause respective losses of US $57.6 and US $43.8 billion/year in eight major crops, including cereal staples (Nwilene et al., 2008; Savary et al., 2019). For decades, endemic pests such as brown planthopper or blast and blight diseases constrain Asian rice production (Bottrell and Schoenly, 2012), while beet armyworm, diamondback moth, vegetable leaf-miners or the eggplant fruit-borer degrade the harvest quality and quantity of myriad other food crops (Waterhouse, 1998). Their incidence, severity and impact vary considerably between growing seasons, crop typologies, geographies and pest taxa. For example, stemborers regularly cause up to 95% losses in India or Indonesia, but only lower Philippine rice yields by 7% (Yudelman et al., 1998; Savary et al., 2019). While endemic organisms account for some of these productivity losses, global trade increasingly facilitates the proliferation of non-native herbivores (Diagne et al., 2021). As a result, invasive pests presently inflict agricultural losses worth US$30 billion per year across Southeast Asia (Nghiem et al., 2013) and over US $100 billion in China (Paini et al., 2016). Notwithstanding their monetary value, food security implications and societal impacts (e.g., Burra et al., 2021), regionally coordinated risk assessment, prevention or control of these transboundary pests is sorely lacking.

Yet, there is considerable scope for national governments to step up the proactive management and deterrence of transboundary pests. Pest-induced losses can be averted by tightened biosecurity and due vigilance, by restoring the ecological resilience of farming systems and by consciously prioritizing management tactics such as biological control (Bommarco et al., 2013; Diagne et al., 2021). For invasive and endemic pests alike, on-farm biodiversity can be harnessed to raise pest mortality levels and curb pest-induced losses (Horrocks et al., 2020). Where relevant, judiciously selected exotic organisms can be introduced to suppress invasive pests (Wyckhuys et al., 2020b), while enhancing (field or farm-level) functional diversity can simultaneously boost pest control and crop yield (Barnes et al., 2020; Tamburini et al., 2020). Varietal resistance, habitat manipulation and semiochemicals equally fortify the resilience of agro-ecosystems (Egan and Chikoye, 2021). These measures either directly favor resident natural enemy populations (e.g., hedgerows, field margins; Garratt et al., 2017; Gontijo, 2019) or lower pest pressure without resorting to synthetic biocides (e.g., crop varietal mixtures, behavior-modifying volatiles; Zhu et al., 2000; Kirk et al., 2021), thus retaining agro-ecosystem functionality.

All these practices are core constituents of integrated pest management (IPM; Naranjo, 2011; Pecenka et al., 2021); a globally valid decision framework that underlines the role of (agro-ecological) avoidance tactics in delaying or preventing pest build-up. By pairing such avoidance measures with a drastic reduction (or total phase-out) of pesticide use, one can avoid the emergence of secondary pests, pest resurgence and a gradual erosion of natural pest regulation (Geiger et al., 2010). During the 1980–90s, UN-funded programs promoted IPM in multiple Asia-Pacific countries. However, their achievements have largely been undone (Bottrell and Schoenly, 2012; Thorburn, 2015; Prihandiani et al., 2021) and pesticide imports now annually increase by 55–61% in countries such as Cambodia or Laos (Schreinemachers et al., 2017). More so, pesticide-related risks have become especially pronounced in Malaysia, the Philippines or Vietnam's river deltas (Tang et al., 2021). To mitigate pest-induced impacts and pesticidal pollution, government actors have an important role to play. By defining adequate policies and through targeted investments in priority IPM initiatives, crop protection science can be effectively wedded to technology transfer, farmer education and behavior change (Wyckhuys et al., 2020a). These elements are especially important as farmers often find themselves unprepared to tackle invasive pests or hesitant to opt for non-chemical solutions (Upadhyay et al., 2020; Bakker et al., 2021). Inclusive, multi-country assessments of national IPM programs and linked policy frameworks are thus exceptionally valuable but are rarely conducted (Handford et al., 2015). Instead, (expert) evaluations of IPM schemes are routinely centered on one or few commodities, management tools or biotic constraints (Vasileiadis et al., 2011; Veres et al., 2020).

In this study, we conduct a diagnostic assessment of national plant protection programs across the Asia-Pacific. More specifically, we aim to gauge their maturity, inclusiveness and ability to take proven IPM technologies to scale. Aside from identifying key TPPs, strategic directions and programmatic priorities at a regional level, our work characterized individual countries' strengths and weaknesses in the promotion of sustainable crop protection. Throughout the manuscript, we primarily use the term "pest" to refer to crop-feeding animals (i.e., pests as compared to pathogens) but also occasionally use this term when discussing the full suite of TPPs. Our findings can help to tailor development assistance to countries' needs, identify opportunities for inter-country cooperation and define specialized training courses to fill capacity gaps.

MATERIALS AND METHODS

To gather the underlying data for the study, a structured questionnaire was developed targeting the 25 national plant protection organizations (NPPOs) that constitute the FAO-hosted Asia Pacific Plant Protection Commission (APPPC). The questionnaire contained a total of 30 multi-part questions (**Supplementary Information**), comprising both close-ended (i.e., multiple-choice, rating scale) and open-ended questions. The (25) formally assigned NPPO country representatives were invited to complete the survey in a collaborative manner with relevant staff of their institution, returning one consolidated answer. The target population for the survey thus comprised more than just the initial contact persons, but covered (variable, yet undefined) numbers of national program staff. Survey questions were posed in English, but national program staff were encouraged to translate these questions into local languages where deemed relevant and necessary. While being mindful of the time constraints of national staff, the survey aimed to receive (at least partially) complete responses from all 25 NPPOs in the region. The survey intended to systematically review the plant protection programs within each of the Asia-Pacific countries, characterizing its core areas of intervention, management strategies and relevant policies. As such, the survey allowed defining country-specific strengths, weaknesses and related opportunities for capacity development or inter-country cooperation.

More specifically, survey respondents were invited to elaborate on priority TPDs, strategic directions within their country's IPM program, the degree of attention that is presently given to themes such as basic, applied and participatory research, and the status of their farmer extension programs. Arable weeds were not covered in the survey. For each country, the online survey also gauged the (perceived) socio-economic relevance of certain transboundary pests and assessed whether the plant protection program was properly aligned with the IPM conceptual model (Naranjo, 2011). Respondents were asked to describe which degree of importance is given to 10 different IPM constituent components in their national plant protection program and to craft their own "model" IPM program. The IPM constituent components comprised (1) integrated resistance management (IRM); (2) efficacious pesticides; (3) pesticide use decision criteria and thresholds; (4) pest / disease detection and sampling protocols; (5) habitat and landscape management; (6) varietal resistance; (7) biological control; (8) mechanical and physical control; (9) cultural control; and (10) pest or disease bio-ecology.

A separate section within the questionnaire equally intended to gauge respondents' perspective on specific topics such as pesticide-centered crop protection vs. biological control or top–down vs. bottom-up extension approaches (e.g., Röling and Van De Fliert, 1994). Lastly, a set of questions aimed at identifying different barriers to the uptake and diffusion of IPM preventative tactics such as biological control. More specifically, respondents were asked to rank the relative importance of seven socio-technical pillars as obstacles of IPM diffusion (Deguine et al., 2021): (1) knowledge; (2) user preferences; (3) infrastructure; (4) industry; (5) technology; (6) policy and (7) culture. Respondents were equally asked to elaborate how biological control compared to pesticide-based approaches in terms of five different technology attributes i.e., relative advantage, compatibility, complexity, observability and trialability. These attributes are thought to shape the on-farm adoption and community-wide diffusion of specific technologies including overall IPM packages and their individual constituent components (Rogers, 1962).

The questionnaire was pretested with two former NPPO country representatives, refined with assistance from plant protection experts of the UN Food and Agriculture Organization (FAO) and transferred to an online survey format. Despite this internal revision and careful fine-tuning of the questionnaire, the survey tool likely still presents some (unforeseen) shortcomings and limitations. In February 2021, the survey was circulated through the SurveyMonkey cloud-based platform among the country representatives of each of the 25 NPPOs that operate under APPPC. Respondents were allotted between 2 and 3 weeks to complete the online questionnaire, and one reminder email was sent to non-respondents 1 week prior to the deadline. For each NPPO, only one (consolidated) response was received for further analysis.

RESULTS AND DISCUSSION

The online questionnaire was (partially) completed by respondents from 11 Asia-Pacific countries i.e., Brunei Darussalam, Cambodia, China, Indonesia, Malaysia, Myanmar, Nepal, Philippines, Singapore, Thailand and Vietnam. Yet, only eight countries consistently answered all survey questions. This low response rate potentially can be attributed to survey fatigue and an increased load of (online) tasks during the COVID-19 pandemic.

Except for Laos and East Timor, the survey thus covered all of mainland and maritime Southeast Asia. While the survey was completed by a multi-disciplinary team of national program staff in certain countries, only one individual acted as a designated representative of the country's NPPO in others. Hence, survey responses do not necessarily reflect the official stance of a country's plant health authority.

Pest and Disease Priorities

Survey respondents were asked to enumerate TPDs that are specifically targeted or prioritized under NPPO's national plant protection programs. A total of eight countries provided a full or partial listing of the agricultural pests and diseases that were covered by their plant health program. Twenty-three different diseases were enumerated (**Table 1**)—a respective 6, 11, and 5 associated with bacterial, fungal and viral pathogens. Among these, 42% were biotic constraints of cereal crops i.e., rice, wheat, barley or corn. Transboundary diseases and causal pathogens that were listed by multiple countries included rice blast fungus (*Magnaporthe grisea*), rice bacterial blight (*Xanthomonas oryzae* pv. *oryzae*), wheat yellow rust (*Puccinia striiformis* f. sp. *tritici*), potato late blight (*Phytophthora infestans*), Panama disease (*Fusarium oxysporum* f. sp. *cubense*) and citrus greening disease (*Candidatus Liberibacter* spp.). The latter disease is caused

TABLE 1 | Common plant disease targets and priority foci, as enumerated by different Asia-Pacific countries.

Taxonomic classification	Disease	Main host	# Target diseases	# priority foci
Bacteria: Acholeplasmatales	Maize bushy stunt phytoplasma	Corn	1	1
Bacteria: Burkholderiales	Bacterial panicle blight	Rice	1	1
Bacteria: Burkholderiales	Bacterial wilt	Potato, vegetables	1	-
Bacteria: Rhizobiales	Citrus greening disease	Citrus	3	1
Bacteria: Xanthomonadales	Black rot	Vegetables	1	-
Bacteria: Xanthomonadales	Rice bacterial blight	Rice	2	2
Fungi: Cantharellales	Wheat sharp eyespot	Wheat	1	-
Fungi: Cantharellales	Dry root rot	Sesame	1	1
Fungi: Capnodiales	Corn gray leafspot	Corn	1	1
Fungi: Capnodiales	Citrus leafspot	Citrus	1	1
Fungi: Hypocreales	Fusarium head blight	Wheat, rice, barley	2	1
Fungi: Hypocreales	Panama disease	Banana	2	2
Fungi: Magnaporthales	Rice blast fungus	Rice	5	3
Fungi: Peronosporales	Downy mildew	Multiple crops	1	-
Fungi: Pucciniales	Coffee rust	Coffee	1	-
Fungi: Pucciniales	Wheat yellow rust	Wheat	2	1
Fungi: Peronosporales	Potato late blight	Potato	2	1
Protists—Plasmodiophorales	Clubroot	Vegetables	1	1
Virus—Geminiviridae	Chili leaf curl disease	Vegetables	1	1
Virus—Geminiviridae	Cassava mosaic virus	Cassava	1	-
Virus—Martellivirales	Citrus tristeza virus	Citrus	1	-
Virus—Ortervirales	Tungro virus	Rice	2	1
Virus—Reovirales	Rice ragged stunt virus	Rice	1	-

Diseases are indicated with their common name. The full list is drawn based upon (complete or partial) inputs from eight countries i.e., China, Indonesia, Malaysia, Myanmar, Nepal, Philippines, Singapore and Thailand. Four plant diseases of common concern among different countries are highlighted. Numbers in the table are indicative of the number of survey respondents that list a given organism either as a target or priority focus.

by an insect-vectored plant virus that is transmitted by at least one endemic species of psyllid (Halbert and Manjunath, 2004), thus being of mutual concern to plant pathologists and entomologists.

Similarly, a total of 55 animal species (or genera) were listed as economically relevant pests (**Table 2**). Among these, respondents enumerated 51 species of insect herbivores (6 orders) that mostly belong to the Lepidoptera or Hemiptera. Though 11 different herbivores affected rice, the overall range of afflicted crops included a myriad of (perennial) fruits, vegetables, root and tuber crops, and livelihood security crops such as coconut, coffee or cocoa. Pests of common concern comprised endemic organisms such as *Eriophyes litchi* (litchi mite) or *Nilaparvata lugens* (brown planthopper), cosmopolitan species such as *Bemisia tabaci* (silverleaf whitefly) or *Plutella xylostella* (diamondback moth), and invasive species such as *Tuta absoluta* (tomato pinworm) or *Neoleucinodes elegantalis* (eggplant moth). Several of the invasive species (e.g., the recently arrived *T. absoluta* and *Spodoptera frugiperda*) are of Neotropical origin. Pests of priority concern to multiple countries included *S. frugiperda*, *N. lugens*, Asian corn borer (*Ostrinia furnacalis*) and a speciose complex of *Bactrocera* sp. fruit flies. Lesser degrees of attention were given to *T. absoluta*, *P. xylostella*, *Liriomyza* sp. leafminers, beet armyworm (*Spodoptera exigua*), striped rice stemborer (*Chilo suppressalis*) or rats.

When asked to quantify TPD-related economic damage, survey respondents estimated percentual yield decline and the ensuing economic losses in their respective countries. On average, animal pests and plant pathogens were believed to jointly cause 20–35% yield losses. Survey respondents considered that pest-induced crop losses were worth between US$300 (staple crops, China) and US$5,000 per hectare and year (Malaysia). In addition, expenditures for pest control were estimated to range between US$25-50 (Nepal) and US$2,250/ha/year (shallot, Indonesia). In Cambodia, farm-level expenditures for pest control were thought to range between US$40-50/ha for dry-season rice and US$180–200/ha for vegetables. The latter value likely reflects reality as Cambodian vegetable growers spend approx. US$230/ha/cycle on chemical pesticides-—92% of which is overspent (Schreinemachers et al., 2020). Respondents from 11 Asia-Pacific countries ranked TPPs' socio-economic impacts fairly high, at 59 ± 33 on a scale from 0 to 100 (x ± SD; 100 being major impacts). However, countries did vary greatly in their perceptions, with Thailand (ranking: 11) and Brunei (12) perceiving crop pests or diseases to be of limited importance. Conversely, Nepal and Malaysia assigned a value of 100 to TPP threats—thus underlining their major socio-economic relevance.

TABLE 2 | Common herbivorous pest targets and priority foci, as enumerated by different Asia-Pacific countries.

Taxonomic classification	Pest species	Main host	# Target pests	# Priority foci
Acari: Trombidiformes	*Eriophyes litchi*	Litchi	1	–
	Tetranychus spp.	Multiple crops	2	–
Insecta: Coleoptera	*Cosmopolites sordidus*	Banana	1	–
	Dorylus orientalis	Potato	2	2
	Dorysthenes buqueti	Sugarcane	1	–
	Phyllophaga spp.	Maize	1	1
	Rhynchophorus ferrugineus	Coconut	1	1
	Sternochetus frigidus	Mango	1	1
	Xylotrechus quadripes	Coffee	1	–
Insecta: Diptera	*Bactrocera* spp.	Fruits, vegetables	6	5
	Liriomyza spp.	Potato, vegetables, legumes	2	1
	Procontarinia sp.	Mango	1	1
Insecta: Hemiptera	*Aphis fabae*	Potato, vegetables, legumes	1	–
	Aspidiotus destructor	Orchard crops	1	–
	Bemisia tabaci	Vegetables	2	–
	Cicadella viridis	Rice	1	–
	Dalbulus maidis	Corn	1	–
	Drosicha mangiferae	Mango	1	–
	Ferrisia virgata	Orchard crops	2	–
	Holotrichia spp.	Sugarcane, legumes	1	–
	Myzus persicae	Potato, vegetables	1	–
	Nephotettix spp.	Rice	1	–
	Nilaparvata lugens	Rice	4	4
	Phenacoccus madeirensis	Orchard crops	1	–
	Phenacoccus manihoti	Cassava	1	–
	Pseudococcus jackbeardleyi	Orchard crops	1	–
	Rhopalosiphum padi	Wheat, barley	1	–
	Sitobion miscanthi	Wheat	1	–
	Schizaphis graminum	Wheat, pearl millet	1	–
	Sogatella furcifera	Rice	1	1
	Idioscopus clypealis	Mango	1	–
Insecta: Lepidoptera	*Chilo suppressalis*	Rice	3	–
	Cnaphalocrocis medinalis	Rice	1	1
	Conopomorpha cramerella	Cocoa	1	1
	Eudocima phalonia	Citrus, perennial fruits	1	–
	Helicoverpa armigera	Corn, vegetables	1	1
	Keiferia lycopersicella	Tomato	1	1
	Leucinodes orbonalis	Eggplant	1	2
	Leucania loryi	Rice, corn, wheat	1	-
	Mythimna separata	Rice, sorghum, corn	1	-
	Neoleucinodes elegantalis	Tomato, eggplant	1	1
	Opisina arenosella	Coconut	1	–
	Ostrinia furnacalis	Corn	3	2
	Plutella xylostella	Cabbages	2	2
	Scirpophaga incertulas	Rice	1	1
	Scirophaga innotata	Rice	1	1
	Spodoptera exigua	Potato, legumes, vegetables	2	2
	Spodoptera frugiperda	Corn	8	8
	Spodoptera litura	Cotton, vegetables	2	–
	Tuta absoluta	Tomato	2	2
	Virachola isocrates	Orchard crops	1	–

(Continued)

TABLE 2 | Continued

Taxonomic classification	Pest species	Main host	# Target pests	# Priority foci
Insecta: Orthoptera	*Locusta migratoria*	Multiple crops	1	–
Insecta: Thysanoptera	*Thrips palmi*	Vegetables	1	1
Mammalia: Rodentia	*Ratus* spp.	Rice	2	2
Nematoda: Tylenchida	*Meloidogyne* spp.	Multiple crops	1	–

Pests are indicated with their scientific name. The full list is drawn based upon (complete or partial) inputs from eight countries i.e., China, Indonesia, Malaysia, Myanmar, Nepal, Philippines, Singapore and Thailand. Four pests of common concern among different countries are highlighted. Numbers in the table are indicative of the number of survey respondents that list a given organism either as a target or priority focus.

IPM Program Outline

Respondents from 10 countries confirmed their familiarity with integrated pest management (IPM). When asked to freely describe features of their country's plant protection program, equal degrees of attention were given to the various IPM constituent components. Chemical control was free-listed by 6 (out of 9) countries, (pheromone-based) trapping and surveillance by 5 countries and avoidance tactics (i.e., varietal resistance, biological or cultural control) by 4-5 countries. The role of stakeholder education was generally disregarded, as only 2 (out of 9) respondents considered this to be a central feature of their country's programs. Overall, national programs were well-aligned with the IPM conceptual model or so-called "IPM pyramid" (Naranjo, 2011). Across ten countries, varietal resistance and sanitation and cultural control were reported to be cornerstones of national IPM programs (**Figure 1**). While pesticide efficacy screening received priority attention (ranking 8/10; 10 being top priority), national programs did not develop the decision-criteria to ensure that their farm-level use is also rational, targeted and economically justified (Pedigo and Rice, 2014). Within the bundle of IPM avoidance tactics, comparatively little attention was given to (pest, disease) bio-ecology and landscape management i.e., foundational elements of IPM. Programmatic priorities differed between individual countries, with certain countries being more technocentric while others favored agro-ecological approaches. For instance, Nepal prioritized cultural and mechanical control. Meanwhile, Thailand placed most weight on selecting efficacious pesticides and varietal resistance. These varying priorities can either be ascribed to external influences, domestic capabilities or misguided perceptions among key decision-makers (Deguine et al., 2021).

When asked to design their own "model" IPM program, responses were received from 7 different countries. Overall, chemical use received considerably less attention in "model" programs as compared to those under actual implementation (**Figure 1**). While pesticide efficacy screening was prioritized in existing plant protection programs, this component was invariably downgraded (ranked 2.6/10; 0-10 scale with 1 being the lowest priority) in respondents' depiction of a "model" IPM program. Moreover, priority components in such "model" programs were varietal resistance (ranked 8.4/10), cultural control (7.4), pest detection and sampling (7.0) and mechanical control (6.1). Respondents equally recognized the value of characterizing pest or disease bio-ecology (ranked 6.0/10). Regarding chemical control, "model" IPM programs emphasized the importance of decision criteria and thresholds (4.9). Lastly, respondents placed more weight on biological control (5.3/10) than any of the three pesticide-related components (1.9-4.9). Hence, although plant protection staff recognize how (non-chemical) avoidance measures and decision criteria are core IPM components, their importance is invariably downplayed within current plant protection programs.

Individual countries differed in their depiction of a "model" IPM program (**Figure 1**). Thailand, Indonesia, China and the Philippines all perceived IPM as a "pyramidal approach" underpropped by a suite of non-chemical avoidance measures. While China and the Philippines placed relatively more weight on pest detection and diagnostics, the other two countries considered pest or disease bio-ecology to be the foundation of robust IPM schemes. Malaysia and (partially) Nepal placed comparatively more emphasis on effective chemical control and downplayed the role of habitat or landscape management, thereby somewhat tilting the IPM "pyramid" (**Figure 1**). Meanwhile, Malaysia assigned the highest degree of importance to application thresholds and decision criteria i.e., central features of an IPM program (Pedigo and Rice, 2014). These institutional stances, perceptions and beliefs constitute a valuable starting point for a future strengthening or entire overhaul of country's IPM programs.

Farmers' Pest Management

Smallholders play a pivotal role in Asia–Pacific agri-food production, with roughly 11, 20 and 37 million (primarily small-scale) farmers operating in Myanmar, Vietnam or Indonesia, respectively (FAOSTAT, 2021). Respondents from eight countries unanimously indicated how pesticide use has become a central pillar of farmers' pest management. To far lesser extent, farmers are thought to use biological control and biopesticides (5 countries), cultural control, e.g. adapted planting date, row spacing or fertilizer use (5), pest-resistant varieties (3) and sanitary measures (2). Lastly, farmers are deemed to lag in their adoption of landscape or habitat management, field-level scouting and trapping, and semio-chemicals. Yet, irrespective of their reliance upon one or more IPM constituent components, farmers were resolutely labeled as "IPM-adopters". This may reflect how the IPM concept possibly has been diluted and is

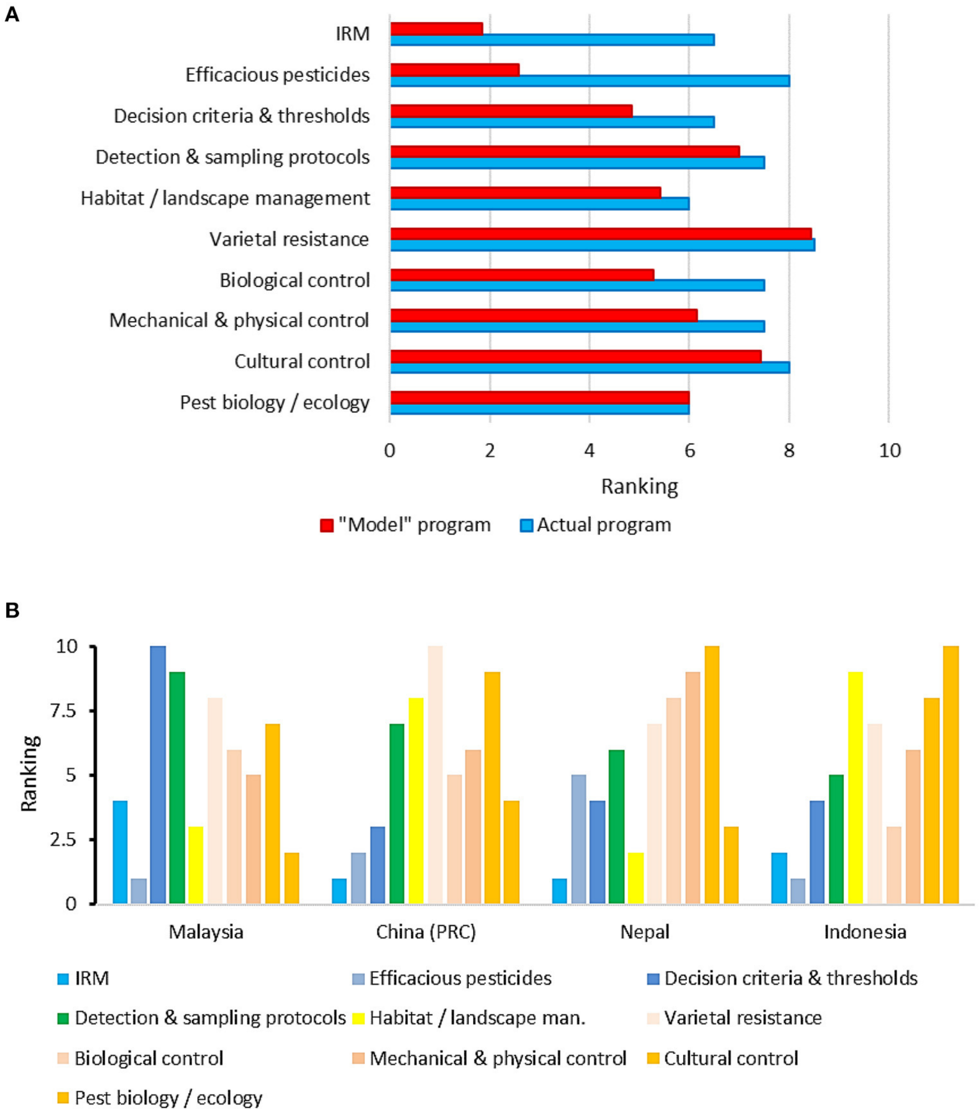

FIGURE 1 | Lay-out of the current and "model" IPM program, as envisioned by respondents from seven Asia-Pacific countries. Panel A shows consolidated patterns for the current and "model" IPM program of all countries, while Panel B depicts "model" IPM programs for four specific countries. Individual components are ranked in accordance with the IPM conceptual model or "pyramid" (Naranjo, 2011). In **(A)**, different ranking scales were used to assess the relative composition of current and "model" programs. In **(B)**, the length of each bar mirrors the relative degree of attention a given component merits within a comprehensive IPM program. Color-schemes reflect whether components constitute avoidance tactics (yellow; base of the IPM pyramid), sampling (green) or effective chemical use (blue). IRM refers to insecticide resistance management.

being re-framed as "integrated pesticide management" (Ehler, 2006).

Respondents varied in their assessment of farmers' pest management behavior and the extent of pesticide over-use in their respective countries (**Figure 2**). On a scale of 0-100, respondents ranked farmers' current practice (i.e., 100 being "very good") and their dependency on synthetic pesticides (i.e., 100 being 'extensive use'). Though farmers' practices were ranked favorably at 63.0 ± 21.2 (x ± SD; $n = 9$), respondents invariably expressed concern about the degree of pesticide use (ranked at 68.1 ± 25.9; $n = 9$). Respondents from Nepal, the Philippines, Indonesia and Singapore perceived farmers' management practices to be defective. Similarly, respondents from Thailand, Malaysia and Cambodia recognized pesticide over-use as a major issue. These concerns are warranted, as Malaysia exhibits the 13th highest pesticide use intensity worldwide (7.7 kg/ha per year; FAOSTAT, 2021). China, Vietnam and Thailand are marked by similarly high usage levels—assuming a respective 23th, 40th and 47th position globally. Thus, in countries where farmers' pest management is deemed to be faulty and pesticide over-use issues are acknowledged, there may be scope for agro-chemical reduction programs. As such, Cambodia, Malaysia and Indonesia could be fertile grounds for renewed IPM campaigns like the

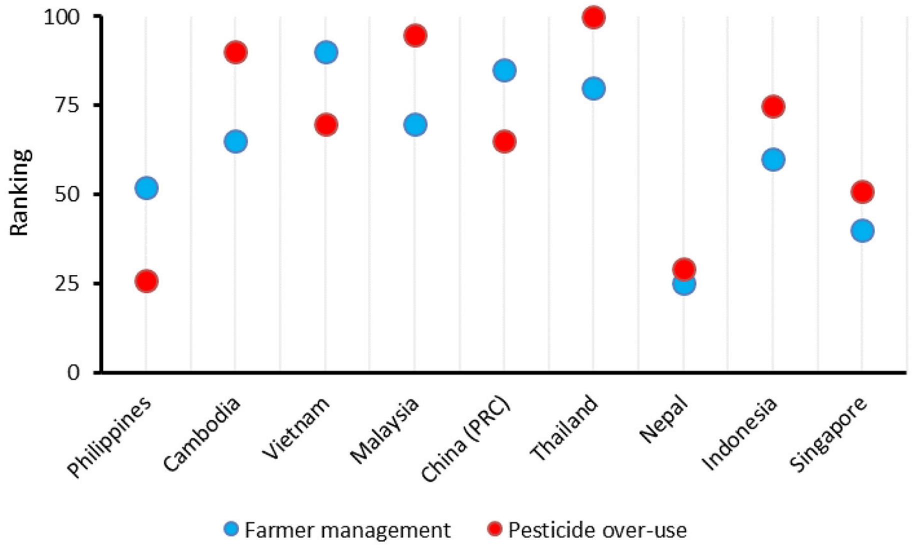

FIGURE 2 | Country-level perceptions regarding farmers' pest management and the extent of pesticide over-use. Patterns are plotted for nine different Asia-Pacific countries. Both variables are ranked on a scale from 0 to 100, with 100 either reflecting "very good management" or "significant over-use".

ones conducted in the 1990s (Van den Berg and Jiggins, 2007).

Several of the above patterns were corroborated when individual countries free-listed options to amend farmers' management. In terms of desired improvements, decision-support tools (3 countries), concrete pesticide reduction strategies (3), non-chemical crop protection (2) and pest detection and diagnostics (2) were regularly put forward. In China and Nepal, respondents placed more emphasis on safe and rational use of pesticides—emphasizing training on (need-based) pesticide applications, personal protective equipment (PPE) or different active ingredients (AIs), dosage and application modes. Only five (out of 9) country respondents believed that their farmers are properly equipped to manage TPPs in a sustainable, safe and environmentally responsive manner. Among five IPM constituent components, farmers were thought to be knowledgeable about sanitary practices (average ranking 72/100; 100 being very knowledgeable) and pest-resistant varieties (67/100). Similarly, farmers reportedly had some understanding of biological control (56/100) but were largely unaware of economic thresholds and sampling protocols (both 33/100). More so, 30% of respondents signaled that local farmers possessed no understanding of the latter two topics. On biological control, only Philippine farmers were believed to possess advanced levels of knowledge. Good farmer practice was ascribed to comprehensive training programs (Malaysia) and a close collaboration with pest observers and extension officers (Indonesia).

Respondents from all nine countries underscored a need for well-designed, comprehensive farmer education schemes. At present, country-level IPM training programs annually reach a respective 10,000; 10-20,000; 20,000; and more than 10 million farmers in Cambodia, Malaysia, Nepal and China, comprising dynamic hands-on activities and more static lectures on a range of topics. Participatory training initiatives (i.e., farmer field schools FFS; Röling and Van De Fliert, 1994) reportedly cover between 2-5% (Malaysia, Nepal) and 100% of all trained farmers (Cambodia, China). In other countries, farmer training programs are relatively small (Vietnam), have recently been downscaled (Philippines) or follow a more 'hands-off' approach e.g., by distributing instructional leaflets or IPM information brochures (Singapore). Less than half of the countries pursued an active involvement of women in IPM training activities and crafted their training programs accordingly. Respondents from eight (out of 9) countries recognized how a close, two-way farmer-scientist interaction can help to adapt IPM technologies to farmers' needs and eventually enhance their diffusion rates.

IPM Adoption Barriers

When promoting IPM, various socio-technical factors can hinder progress (Deguine et al., 2021). Upon estimating the relative importance of 7 socio-technical pillars as IPM obstacles, respondents from nine countries unanimously assigned the highest ranking to a "knowledge" pillar. This mirrors how insufficient knowledge of farmers, plant protection officers and extension personnel or a deficient understanding of agro-ecosystem dynamics hamper IPM adoption. Respondents equally considered "policy", "user preferences" and the (perceived) immature nature of IPM technologies to be prime obstacles. Comprehensive policies that are attuned to local conditions and that encompass different value chain actors are crucial in the promotion of IPM, as also evidenced by experiences in Indonesia (Thiers, 1997; Möhring et al., 2020). User preferences capture stakeholder attitudes toward certain pests or crop protection measures, peer pressure or farmers' risk-averse behavior. The latter directly relates to farmers' lack of familiarity with effective, non-chemical alternatives (Gent et al., 2011; Wyckhuys et al., 2019). Only 30% of respondents perceived industry interference as a major hurdle in the IPM diffusion process, thus potentially underestimating the reach and influence of these powerful actors (Goulson, 2020).

Respondents deemed that TPPs could be effectively managed with a 37.5 ± 33.4% (x ± SD; $n = 6$) lower use of pesticides, with 50–100% pesticide reductions thought to be feasible in Malaysia and the Philippines. These drastic reductions may be realistic, given that UN-directed IPM programs during the 1990s lowered insecticide use in Indonesia rice, Vietnam rice, Bangladesh eggplant or India cotton by 61, 82, 80 or 78% respectively (Van den Berg and Jiggins, 2007). Respondents further considered that there was ample scope to reduce pesticide usage in (paddy) rice, vegetables, maize, tropical fruits and potato.

Biological control and agro-ecological preventative measures (e.g., cultural control, sanitary measures) constitute the foundation the IPM pyramid i.e., as compared to synthetic pesticides which are placed at the top of the pyramid. The diffusion of these former two technologies is dictated by their (perceived) relative advantage, compatibility, complexity, observability and trialability (Rogers, 1962). Respondents of nine countries felt that (microbial, invertebrate) biological control did not present any clear, unambiguous disadvantage over synthetic pesticides (**Figure 3**). Yet, biological control was deemed to be less compatible, observable or trialable, and slightly more complex. In the absence of corrective measures, stakeholder education and awareness-raising, the latter four attributes can thus make biological control comparatively less likely to succeed and attain broad-scale adoption. Adoption rates of certain forms of biological control can also be constrained by its availability and affordability for resource-poor smallholders (Constantine et al., 2020). Carefully assessing these limitations through a 'diffusion of innovations' lens can help bridge the research-practice gap and increase its uptake (Barratt et al., 2018). Similarly, preventative measures such as agro-ecology tend to diffuse slowly due to delayed rewards for early adopters. To aid their diffusion, one can change their perceived attributes, engage so-called "champions" in their promotion, alter the norms of the relevant social system, wield entertainment–education or mobilize peer networks (Rogers, 2002). These above approaches carry considerable value to promote IPM and biological control in the Asia-Pacific region and across the globe.

On the other hand, respondents from nine countries routinely perceived biological control to be more advantageous than chemical control for different socio-economic and 'planetary health' outcomes (Horton and Lo, 2015). On a scale from −2 to 2 (−2 being "noticeably worst"; 2 being "noticeably better"), biological control ranked 1.9 ± 0.3 (x ± SD) for biodiversity conservation, human health and water safety or quality. In terms of food safety, biological control ranked 1.6 ± 0.5 and thus equally outperformed pesticide-based approaches. By systematically documenting and communicating these diverse societal benefits (e.g., Bale et al., 2008; Burra et al., 2021), one likely can attain a tipping point in the uptake of biological control. This potentially can enable transformative change, with non-chemical pest management becoming the norm instead of the exception.

Decision Support Tools

Action thresholds or economic thresholds (ET) constitute the backbone of an IPM program (Pedigo and Rice, 2014). These decision-support tools provide crop-, pest- and locality-specific information on the injury level at which curative (pesticide-based) intervention is warranted and economically justified. Locally validated thresholds thus help to rationalize pest management, avoid superfluous pesticide expenditure and minimize its social-environmental impacts. Unexpectedly, China and Thailand are the only countries where more than two (pest-specific) ETs have been incorporated into the national IPM policy. Fifteen 15 ETs are promoted in China while 6 ETs have been defined in Thailand; the latter targeting rice pests such as *Chilo suppressalis*, *Nephotettix virescens* or *Nilaparvata lugens* and vegetable pests such as *Bemisia tabaci*, *Liriomyza brassicae* or *Thrips palmi*. Overall, ETs are validated and communicated for a fraction of pests or diseases of cereals and horticultural crops e.g., cabbage, tomato, watermelon and potato. ETs are only available for two pests in Cambodia (i.e., rice brown planthopper, diamondback moth), while these decision criteria are outlined per crop instead of per target pest in Indonesia and Malaysia. Several countries (i.e., Philippines, Vietnam or Nepal) do not consider ETs and thereby create fertile ground for pesticide overuse. The development of new ETs for resident pests and a local validation of existing ETs e.g., for cosmopolitan pests such as *S. frugiperda* (Overton et al., 2021) carries considerable promise. Doing so can reduce the (annual) crop protection costs by hundreds of dollars per hectare (Schreinemachers et al., 2020; Yang et al., 2021), mitigate poverty vulnerability and thus raise the livelihoods of countless smallholder producers. Aside from reducing input costs, lowered pesticide spray frequencies also conserve beneficial insects and thus generate lucrative co-benefits e.g., in terms or reconstituted crop pollination (Pecenka et al., 2021).

Crop Protection Science and Innovation

Plant protection science in nine countries presently receives less attention than other science, technology and innovation (STI) fields (ranked −0.6 ± 0.9 on a scale from −2 to 2). The different countries reportedly hold credible scientific capacity in phytosanitary diagnostics, pesticide efficacy screening and socio-economics (**Figure 4**). Across eight priority domains, Thailand (ranked 13/16) and China (10/16) proved most confident about their domestic scientific capability. More specifically, respondents of these countries signaled considerable capacity in (molecular) diagnostics and pest or disease taxonomy. Meanwhile domestic capacity was felt to be deficient in Nepal, Singapore and Cambodia (ranked 4-5/16). Thailand reportedly possessed robust capacity in all domains except for pest or disease epidemiology, bio-ecology and socioeconomics.

The above capabilities relate to the interests and strategic directions of multiple (national, local) stakeholders, but can

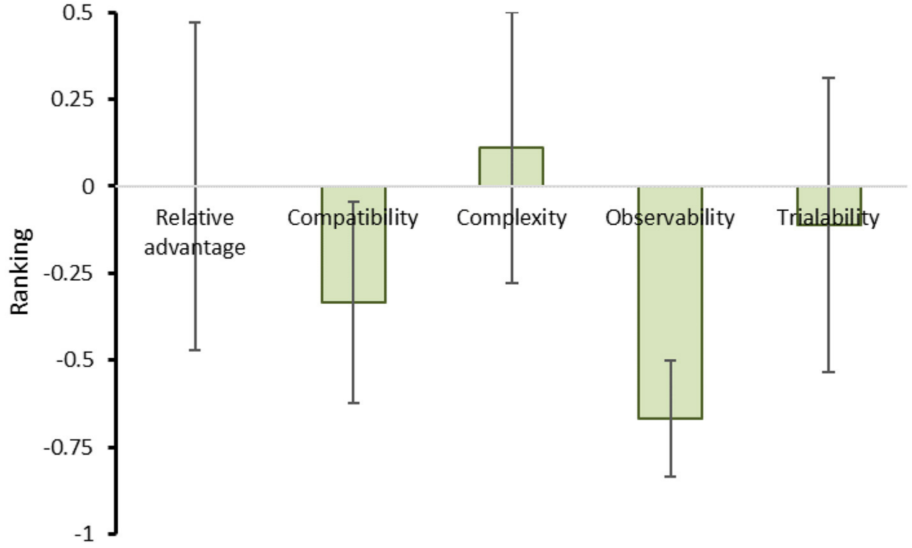

FIGURE 3 | Comparative ranking (x ± SE) of biological control in terms of Rogers' five innovation attributes. For each attribute, respondents from 9 Asia-Pacific countries rank the performance of biological control and biopesticides as compared to synthetic pesticides. Positive values reflect how biological control innovations are perceived to outperform pesticide-based approaches. Attributes are described in further detail in **Appendix III**.

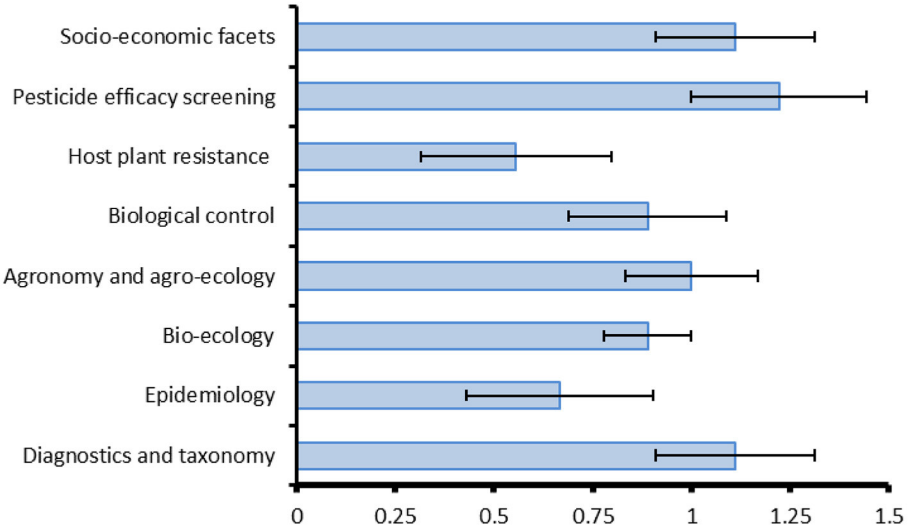

FIGURE 4 | Domestic scientific capability in different plant protection domains, as self-assessed by respondents from nine Asia–Pacific countries. For each of eight key domains, average patterns (x ± SE) are plotted and reflect overall in-country capacity on a scale from 0 to 2 (with 2 being "robust capacity").

equally mirror funding availability. Across the Asia-Pacific, crop protection science was deemed to be critically underfunded; 4 (out of 9) countries signaled how all eight scientific domains faced serious funding shortages. Countries proved least pessimistic regarding the funding status of biological control (ranked 0.7 ± 0.9 on a scale of 0–2) and varietal resistance (0.6 ± 0.5), while funding was lacking for epidemiology (0.3 ± 0.5). Indonesia, Malaysia and China proved least pessimistic on their overall long-term funding prospects for plant protection science. Across countries and domains, public sector contributions and international development assistance made up a respective 81% and 17% of primary funding streams. Development aid was (reportedly) often mobilized for diagnostics, bio-ecology, agronomy or agro-ecology and pesticide screening. Yet, a fair number of international donors (e.g., USAID Innovation lab, NORAD, SIDA or the European Union) likely won't cover the latter.

On a country level, the above funding streams were mapped against domestic scientific capacity and envisioned "model" IPM program structure (**Figure 5**). Although several countries

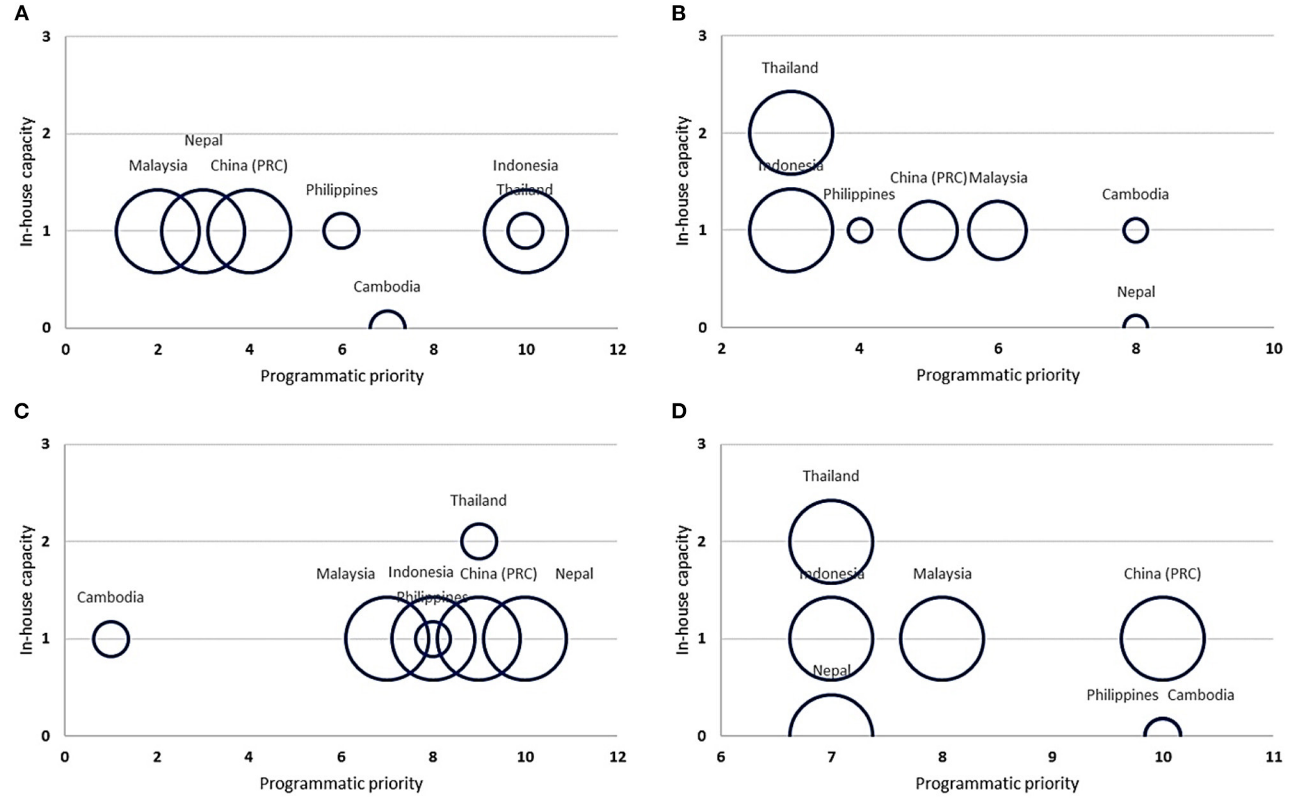

FIGURE 5 | Comparative mapping of domestic scientific capacity, programmatic priority and funding status for 4 crop protection domains in seven Asia–Pacific countries. Plots are drawn for pest/disease biology and ecology **(A)**, biological control **(B)**, agronomy and agro-ecology **(C)** and varietal resistance **(D)**. For each domain and country, bubble size refers to the current funding status (i.e., low, intermediate, high). In all graphs, except for B, the largest bubble size refers to "intermediate funding". Programmatic priorities refer to countries' envisioned "model" IPM framework and are ranked from 0 to 10 (**Figure 1**), while domestic capacity in a given domain is plotted on a 0–2 scale.

TABLE 3 | Mapping of tactical interventions in sustainable crop protection for seven Asia-Pacific countries.

Domain	Country						
	Philippines	**Cambodia**	**Malaysia**	**China**	**Thailand**	**Nepal**	**Indonesia**
Diagnostics and epidemiology	C_r	C_r, F	–	C_p	C_p, F	C_r, F	C_r
Bio-ecology	T, F	T, F	T, R	T	T	R	T
Agronomy and agro-ecology	F	F, R	–	–	C_p, F	–	–
Biological control	C_r, T, F	C_r, T, F	–	–	C_p, R	C_r, T, F	R
Varietal resistance	C_r, F	C_r, F	–	–	C_p	C_r	–
Pesticide efficacy	F	R, F	C_p	–	C_p	C_r, R, F	–

Interventions are proposed for six scientific domains, with "diagnostics and epidemiology" lumping two underlying domains with insufficient data. "Agronomy and agro-ecology" relate to the IPM programmatic components of cultural control and sanitation. Based upon ***Figure 5****, the following interventions are proposed: regional collaboration (C), external technical backstopping (T), bolstered funding (F) or assistance with programme re-design (R). Subscripts 'p' and 'r' refer to countries being a respective provider or receiver of Asia-level support. Countries that potentially can assume a leadership-role in regional initiatives are highlighted in grey.*

identified bio-ecology as a foundational IPM component, they were routinely constrained by low techno-scientific capacity and funding in this domain. Bio-ecology received priority attention in the "model" IPM program of Thailand (i.e., 10/10 ranking), but insufficient domestic capacity and lack of funds prevented this country from fully tapping its potential. While respondents from six (out of 7) countries recognized agronomy or agro-ecology as core features of the IPM "pyramidal" approach (**Figure 5**), only Thailand reportedly possessed solid domestic capacity to take these technologies to scale. Similarly, even though Nepal and Cambodia dedicated priority attention to biological control (**Figure 5**), both countries lacked funds and techno-scientific capacity to effectively deploy it for pest management. Conversely, Indonesia and Thailand possessed major scientific capacity on biological control but downplayed its contribution to IPM programs. Lastly, for the domain of varietal resistance (**Figure 5**), viable funding streams were in place for all countries except Cambodia and the Philippines. The latter two countries and Nepal equally lacked baseline capacity on this IPM component. Based upon this mapping exercise, future development assistance can be delivered in a tailored and potentially more effective fashion. Per country and scientific domain, opportunities could thus be defined for strengthened regional collaboration, technical backstopping, bolstered financial support or assistance with IPM program re-design (**Table 3**).

CONCLUSIONS

This study offers a systematic overview of the strategic directions, inclusiveness and maturity of plant protection programs in 11 Asia-Pacific countries. Based upon an online survey of NPPO representatives, we listed transboundary pests and pathogens (TPPs) that hamper agri-food production across the region, causing direct crop losses and pest control expenditures up to US$5,000 and US$ 2,500 per hectare per year, respectively. These priority TPPs can now become core foci of regionally harmonized initiatives and refurbished IPM programs. As current IPM programs are invariably skewed toward curative (pesticide-centered) control, training programs need to be designed to offer farmers first-hand experience with preventative (non-chemical) tactics e.g., crop sanitation, varietal resistance, habitat management, biological control, field-level scouting or semio-chemicals. Similarly, given that local smallholders routinely overspend hundreds of dollars per hectare on pesticides, economic thresholds need be defined, validated and promoted. Biased stakeholder attitudes e.g., on biological control efficacy are a prominent hurdle in the regional implementation of IPM, and these need to be consciously amended. Notwithstanding the praiseworthy achievements of FFS during the 1990s (Waddington et al., 2014), only a fraction of local farmers is presently involved in participatory training programs. Given the negative societal impacts of pesticide-intensive crop protection, a renewed (regional) push for FFS is imperative. Such effort ideally is to be coupled with digital communication and advisory services (e.g., farmer-to-farmer educational video), policy change and broad awareness-raising e.g., on agroecological measures (Wyckhuys et al., 2022). Both soft and hard policy options, including command-and-control measures, are crucial to restrain pesticide use and take biological control to scale. Countries such as China and Thailand self-identify robust capacity in multiple IPM domains e.g., molecular diagnostics and (pest, pathogen) taxonomy; this capacity is to be tapped and bundled to optimally respond to new or recurrent phytosanitary emergencies. Meanwhile, to defuse invasive threats, globe-spanning professional networks need to be woven and energized (Mason, 2021). Also, by overlaying in-country capacity, funding status and strategic directions of national programs (**Figure 5**; **Table 1**), one can shepherd regional collaboration, tailor technical backstopping or redirect (international) development assistance. We identify ample potential for Thailand to assume a lead role in multiple IPM domains, and for China to take the regional initiative in (pest or pathogen) diagnostics or epidemiology. Meanwhile, Nepal and Malaysia could benefit from program redesign in the bio-ecology domain. Lastly, external backstopping may be required to upgrade the biological control programs of Philippines, Nepal and Cambodia. By thus tactically mobilizing regional capabilities, methodically rerouting country-level IPM programs and creating an enabling (policy) environment, one can ensure that crop protection fully benefits farmers' livelihoods, societal wellbeing and Planetary health throughout the Asia–Pacific.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

KW conceived and designed the experimental approach, collected the data, and analyzed the data. KW, BH, and YG revised the questionnaire and co-wrote the paper. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.853359/full#supplementary-material

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