Technical Report

Bilateral Projects:

Challenge and Opportunity Analysis for an Innovations Hub for coordinative surveillance and early warning for sustainable management of Transboundary Plant Pests (TPPs) in Asia and the Pacific (FAO).

Establishing sustainable solutions to cassava diseases in mainland South-East Asia (ACIAR) and

Plant Health Initiative WP1: *Map of the research and development capacities in SEA for the early detection and sustainable management of Transboundary Plant Pests*

Transboundary plant pests research in Southeast Asia and the Pacific region

Warren Arinaitwe[1], Rafael Rodriguez[1], et al. and Wilmer J. Cuellar*[1]

[1]Cassava Program Crop Protection Team, Crops for Nutrition and Health, International Center for Tropical Agriculture (CIAT)

*Corresponding author: w.cuellar@cgiar.org

Abstract

Transboundary plant pests (TPPs), which can be fungal, viral, bacterial, phytoplasma and insects, are a major hindrance to crop production in Southeast Asia and Pacific (SEA & P) countries. In this part of the world, little is known about TPPs, yet they continue to decimate crop yields. A good example is cassava mosaic disease (CMD), a new disease in SEA & P but well-studied in Africa. CMD was first reported in Cambodia in 2015 in a single field and has since been reported in Vietnam, Thailand, and Laos. As is CMD, many emerging and re-emerging plant diseases in the region remain under-explored. This study examined the current status of TPPs research and potential drivers of TPP research in SEA & P. A combination of secondary (peer-reviewed publications and databases on agricultural indicators) and primary (surveys and focused group discussions) data were used. TPPs research and reporting level in SEA & P countries was low compared to China. It was further found that public spending and human resources-associated attributes influenced TPPs reporting levels in the region. For instance, TPPs reporting increased with the size of R&D investment, researcher full-time equivalents or FTEs, quality of researcher, and investment in physical infrastructure. Our findings show that substantial human and physical infrastructure investment is necessary to enhance TPPs surveillance and reporting in SEA & P.

1.0 Introduction

Outbreaks of new and re-emerging plant pests and diseases increasingly threaten global food production systems [1]. They indirectly impact national security, human health and the livelihoods of millions of people, especially in developing countries [1, 2]. Plant pests and diseases that can spread between landscapes and countries will be referred to as transboundary plant pests (TPPs) throughout this study. TPPs are all organisms that cause disease and can spread into new agro-ecologies or host plants, change pathogenicity or evolve to cause completely new infections in cultivated or wild plants [3, 4]. Lately, the problem of TPPs in agriculture has been exacerbated by climate change, land use changes, and increased

continental movement of agricultural commodities and people [1 and references therein]. Introductions (most likely through global trade and germplasm exchange) and changing weather are the primary drivers of TPPs evolution and geospatial distribution [5, 1]. Introductions account for 56% of emerging TPPs [3, 5, 6]. Recent data suggest a strong correlation between trade and pathogen movement [7]. For instance, the annual arrival rate of plant fungal pathogens in New Zealand increased with import volumes and air passenger arrivals [7]. Also, the overuse of agrochemicals to control old pests and diseases in many farming systems in developing countries, including South and South-East Asia [8], deepens the plant disease crisis by triggering the emergence of new and resistant pests and diseases. The annual economic impact of invasive TPPs is estimated at $540bn [9], and this figure will continue to increase if pathogens associated with TPPs remain unexplored.

Taxonomically, TPP causal agents cluster around fungi, bacteria, viruses, phytoplasma, and nematodes. On a global scale, plant viruses cause 47% of emerging pandemics, followed by fungi (30%), bacteria (16%), phytoplasma (4%), nematodes (1%) and others such as (2%) [3]. Unfortunately, up-to-date, country-level data on the status of economically important TPPs is not well documented in most SEA & P countries. The lack of such data greatly hinders global TPPs management efforts. In this study, we analysed the status of TPPs (using First reports [FR] of a TPPs as a concise and structured source of information), institutional capacity, public spending on agricultural research and some of the interventions (if any) deployed to manage TPPs in SEA & P countries. We used scholarly sites such as Google Scholar and online databases such as IFPRI's Agriculture, Science and Technology Indicators (ASTI) to obtain peer-reviewed reports and long-term data on agricultural research and development indicators. We validated findings from secondary data sources through online polls, focused group discussions and physical observation partners in a few countries, i.e. Laos, Vietnam, and Cambodia. During the survey and physical group discussions, we also collected information on existing institutional capacities, infrastructure, and innovative strategies in force to manage TPPs in Laos, Vietnam, and Cambodia. Finally, partnerships in the region were mapped using network analysis tools.

2.0 Methods

2.1 Secondary data reviews on TPPs research in the region

Using a collection of peer-reviewed articles on first disease and pest reports in Asia published between 2000-2021 in Plant Disease, New Disease Reports, Virus Research and Australasian Disease Notes were analysed to understand the status of TPPs at a continental level (Supplementary data S1). We then narrowed the analysis to SEA & P following the selection described in Fig. 1. A total of 118 first reports (FR) published from 10 countries were selected (Supplementary data S2). Information on host plants, pathogen type (i.e., fungi, bacteria, viruses, phytoplasma, viruses and nematodes) and pathogen identification methods was extracted. Host species affected by specific TPPs were many and highly diverse. To ensure adequate sample sizes to quantify the level of reporting across different pathogen classifications, we pooled host plant species into five groups: 1) staple crops (all cereals, roots and tubers, and pulses); 2) oil crops and other cash crops (sugarcane, coffee, cocoa, rubber); 3) fruit and vegetables; 4) cultivated ornamental crops and 5) weeds. Insect pests FR were not considered in this study. Based on analytical tools (i.e., physical observations, biochemical, serological and molecular) reported by authors in the selected articles, we developed a tier-based proficiency scale (Table 1) to estimate available country-level expertise in TPPs identification. Data processing and exploratory analyses were performed in Microsoft Excel 2010.

To explore factors that may affect TPPs reporting in SEA & P, we obtained numeric data (for the period 2000-2021, where available) from the ASTI database (https://www.asti.cgiar.org/) on public expenditure, human resource investment estimated as full-time equivalents (FTEs) per 100,000 farmers. FTEs estimate the proportion of time researchers spend on R&D compared with other non-research activities such as administration and teaching [10]. FTEs data by qualifications (Supplementary data S3) was used to

generate PhD to BSc ratio. This was used to estimate the quality of human resource investment in TPPs research. Public spending and human resources data were compared with the number of reports per country to check for possible trends. All comparisons were performed in R statistical software.

2.3 Interviews and group discussions

To further understand awareness of TPPs, country-level data on available human resources, infrastructure, existing TPPs management options and collaborative linkages, we focused on three countries, i.e. Laos, Vietnam, and Cambodia. Local scientists were interviewed through a poll (Appendix A1) coupled with virtual and focused group discussions. Information collected included the most essential TPPs by crop, staffing for field, laboratory, and data analysis, and existing infrastructure, i.e., laboratories and screen houses. We also collected information on the use of visual, digital, and molecular tools to analyse TPPs and innovative strategies deployed by different countries to control TPPs effects. Interviewees were also asked to list all partners they have collaborated with in the last five years. For each player, respondents were asked to define the nature of collaboration: financing, exchange of information and germplasm sharing, or co-authorship of publications. Some partners played multiple roles. In the end, a network matrix was created.

3.0 Results

3.1 Research on TPPs is low in Southeast Asia and the Pacific

Using FR as unit of measurement, it was found that the level of TPPs reporting in the SEA & P region is lower compared to neighbour China. Between 2000-2021, 94% of total reports in Asia came from China (Fig. 2A, Fig. 2B; Supplementary data S1**)**. We found that most SEA & P region countries expect Malaysia and Vietnam to publish less than 15 reports between 2000 and 2021. Malaysia has the most significant number of reports (49) followed by Vietnam and Thailand (Fig. 2C). However, in comparison with the number of reports made by China (1801) and Korea (418) (Supplementary data S1), during the same period, each country in SEA & P published less than 10 reports in the last two decades.

3.2 Fungus- and virus-associated TPPs compared to other disease-causing pathogen were more reported in SEA and Pacific countries

One hundred and eighteen FR published between 2000 and 2021 from 10 countries in the SEA & P region were analysed. Our findings showed that the most reported TPPs were fungi (56.7%), followed by viruses (19.5%), bacteria (16.1%), viroids (3.4%), phytoplasma (3.4%) and nematodes (0.8%). Diseases caused by Fungal pathogens ranked highest, followed by viruses and bacteria. Limited studies reported TPPs caused by viroids, phytoplasma and nematodes. The reports varied between countries and host affected (Fig. 3). At country levels, three out of ten countries, i.e., Malaysia, Vietnam and Thailand, dominated in TPPs research and reporting (Fig. 3A). Though the level of reporting was generally low in the region except China, these three countries published more than ten reports on TPPs between 2000 and 2021. The level of reporting also varied by host species affected (Fig. 3B). In decreasing order, the bulk of reports came from fruits and vegetables, cultivated ornamentals, oil crops and other cash crops, staple crops and weeds.

Further analysis of tools used to identify TPPs, which formed an expertise scale (see Table 1), we noted glaring technical differences in expertise depending on the pathogen. Proficiency in using advanced molecular tools singly or in combination was limited, except for culturable bacterial pathogens (Fig. 4). This observation was corroborated by key regional partners from Laos, Vietnam and Cambodia during the poll and discussions. They confirmed that the number of technical staff with expertise in advanced diagnostic and analytical methods is still relatively low. Respondents also indicated inadequacy in laboratory tools and physical infrastructure for timely detection of plant TPPs and other routine pests and diseases (see Table 2).

3.3 Human resource investment and level of public spending are likely potential drivers of poor TPPs reporting in SEA & P

Institutional capacity to collect, identify, analyse and report TPPs is inadequate in most SEA & P countries. The total number of FTEs allocated by agricultural researchers per 100,000 farmers in all evaluated countries except Malaysia has remained lower than 20 and static since 2000 (Fig. 5A). For Malaysia, it steadily increased from about 60 in 2000 to more than 100 FTEs in 2017. We further analysed the FTEs by qualifications in each country. It was found that a large proportion of agricultural research is generated by BSC degree holders than PhD holders than BSc degree holders (Fig. 5B). Previous studies suggest that a high FTEs associated with PhD holders in a research system is critical for research conceptualisation, implementation, analysis and reporting [10]. In SEA and the Pacific, only Malaysia had the highest FTEs by PhD staff. No significant change was noticeable when research intensity (public spending expressed as a share of agricultural GDP) was compared between nations. Still, Malaysia had the highest and most stable research intensity over the study period compared to other countries.

Although the number of FR published is not directly related to the actual number of TPPs affecting a country, it informs on the capacities available to detect, identify and report on a new disease and pathogen. We noted interesting trends when comparing relative reporting per country with the total number of researchers, and researchers' quality and agricultural research intensity using linear models (Fig. 6; Supplementary data S4). Relative reporting per country between 2000 and 2017 was estimated. The regional average number of researchers per 100,000 farmers was 17.9.

There was a strong linear positive association between TPPs reporting and average research intensity ($p < 0.05$; $r^2 = 0.66$). Countries with a high average research intensity published more FR than those with low research intensity (Fig. 6A). Countries with low research intensity and corresponding low reports equivalent were Myanmar, Cambodia, Laos, Indonesia and Papua New Guinea. Similarly, report equivalents per country strongly correlated with average FTEs per 100,000 farmers per year (Fig. 6B). The reporting rate increased with researcher FTEs, suggesting that public spending on recruiting more technical agricultural personnel may directly and positively impact TPPs detection, identification, and reporting. Further dissociation of researcher's FTEs by the level of education confirmed that countries with a high PhD to BSc ratio reported more on TPPs compared to those with a low ratio (Fig. 6C).

Remarkably, import volume did not influence the TPPs reporting levels in the region (Fig. S1). Yet importation of plant-based products is known to enhance the arrival rate of specific pathogens. For instance, increased crop import volumes are strongly correlated with the arrival of fungal pathogens in New Zealand [7]. It is thus plausible that aggregation of host data regarding pathogens detected may have masked the effect of harvested areas and import volume on reporting of specific pathogens. Alternatively, it may be true that crop production and importation parameters may not be a key determinant of TPPs reporting in SEA & P countries. The absence of correlation between import volumes and TPPs reporting should not be celebrated. It may imply that a high proportion of emerging TPPs species go undetectable in the region and may complicate future predictions of crop disease epidemics. Similar observations were made against low detection levels of global invasive species [11].

3.4 Most abundant TPPs in Laos, Vietnam and Cambodia

Cassava, rice, banana, and citrus were reported to be the essential crops across the three countries (Table 3). In cassava, partners ranked witches broom disease (CWBD) and CMD as the most critical TPPs. In rice, farmers in Laos are grappling with Tungro Virus Disease, thought to be transmitted by unknown planthopper. In Vietnam, citrus production is affected by citrus greening disease, a bacterial infection and aphid-transmitted Citrus Tristeza Virus.

3.5 The level of agricultural research staffing and physical infrastructure is inadequate

Analysis of secondary data previously showed that research staffing in the region is low (see Section 3.3). Through an online poll administered to different NPPOs, information on the current number of field, laboratory and data analysis staff were recorded. Preliminary results confirm that staffing in public research institutions is generally low (Table 3). For instance, the total number of laboratory staff in Cambodia, Vietnam and Laos was below 10. Furthermore, a census of physical infrastructure at the four public agricultural research institutions in Cambodia (1), Vietnam (1) and Laos (2) was carried out. Similar to staffing, there are limited facilities to conduct research on TPPs, except in Vietnam, which has 10 research facilities (Table 3).

3.6 Partnerships in TPPs research

Network analysis was used to understand the nature of collaboration between national research institutions and other organisations within and beyond SEA & P. Data on partnerships in monitoring and diagnosing economically important TPPs in the past five years was collected via the poll. Respondents listed their collaborators and the nature of the partnership, which ranged from provision of funding, sharing and exchanging plant germplasm and protocols to exchanging research results and co-authorship of research articles.

Preliminary results show that four major networks exist so far. These networks are represented by four distinct colours in the network matrix shown in Figure 7A**.** The partnerships are rooted in four NPPOs, indicated in the matrix by the large nodes, i.e. PPRI, PPC, GDA and NAFRI-RRI. We noted strong linkages between NPPOs and different development agencies, e.g., FAO and JICA and universities. Exchanging results, samples and technical support ranked highest among the components of partnerships NPPOs benefit from the existing collaborative network (Fig. 7B). Fifty six percent of the respondents showed that they received technical support to identify and combat TPPs in cassava, rice and citrus. Six partners, i.e. FAO, JIRCAS, AFACI, JICA, TTDI and the CGIAR (especially CIAT) provided funding. Noticeably, TTDI (an indigenous Thai entity) is the second-largest donor after CGIAR-associated financing, suggesting that the potential to garner local and regional funding exists.

3.7 Several surveillance technologies and management innovations are being deployed in the region

In the poll and discussions, we solicited information on technologies used to monitor and study TPPs in Laos, Vietnam, and Cambodia. Partners were also followed up via WhatsApp and telephone exchanges, where little information was provided. China, which was included in the analysis as a control. There was limited use of most reliable, high-resolution and rapid tools in the region compared to China (Table 4). For instance, respondents in Laos, Cambodia and Vietnam were unfamiliar with using advanced aerial and underground imaging platforms, GPS-enabled tracking systems and latest molecular tools, such as Nanopore in routine monitoring of TPPs. This was expected as these technologies are costly and require highly skilled operators, which both call for substantial public investments, which is currently short in these developing countries. Limited use of advanced tools is likely impeding rapid management of TPPs in the region. Partners were further interviewed on approaches they have developed or adopted to manage existing and emerging TPPs in their farming systems. Where possible, physical assessments of available innovations were done. We found that Laos, Vietnam and Cambodia exchange surveillance information via an online database, share germplasm and use robust breeding/seed multiplication channels to mitigate the effects of TPPs (Table 5).

3.0 Discussion

The vicious impact of emerging plant diseases, most of which are TPPs, occurs where crop health management systems are poor or underdeveloped [15]. Inadequate investments in fundamental research on disease-causing TPPs largely characterise poor plant health systems. Analysis of peer-reviewed first disease reports in SEA & P in the past two decades revealed inadequacy in basic TPPs research and communication. Out of 2919 FR published in ASIA, only 119 originated from the SEA & P region. It was found that TPPs associated with fungi, and viruses accounted for 77% of the TPPs reported, and the use of advanced TPP identification methods is still at its lowest. The study further shows that poor public investments in required human resources and enabling physical infrastructure such as laboratories, high-precision equipment and tools affected the capacity of NPPOs to monitor, identify and communicate TPPs. This study is the first detailed scoping analysis of TPPs research in the region.

Most SEA &P countries have limited institutional capacity to identify, characterise and report TPPs. Using first disease reports as a proxy indicator for power to investigate and report TPPs, we found that agricultural scientists in most SEA & P countries published less than two reports per year compared to their peers in China between 2000-2021. This is contrary to the predictions in 2014, which hypothesised that over 200 new TPPs would emerge in most SEA countries [16], which may imply that a high number of TPPs might be inconspicuously spreading in the region. Underdiagnosis of TPPs may be due to shortfalls in staffing qualified personnel and lack of required surveillance, diagnostic and prediction tools as recorded in most countries. It requires a functional integrated research agenda to combat the present gap in monitoring, rapid detection, and characterisation of TPPs. Ristaino and others proposed a similar mechanism integrating disease surveillance, improved diagnostics such as pathogen sensors, mechanistic modelling and big data analytics to mitigate future plant disease outbreaks [1].

There is a need to increase FTEs ratio of PhD to BSC in SEA & P. In six out of eight countries surveyed in SEA & P, the PhD to BSC ratio was below 0.5, which may suggest a low number of PhD holders recruited or retained by NPPOs. A considerable proportion of PhD-qualified scientists is generally believed to be critical for conceptualising, executing, and managing high-quality research. It is also vital for effective communication with policymakers, donors, and other stakeholders at local and international meetings. A high proportion of PhDs may also increase the probability of winning competitive funding grants. Our interactions with local scientists in Laos and Cambodia revealed that public sector salaries are generally low, making recruitment and retention of highly competent technical staff difficult. Our findings agree with the most recent report on agricultural research indicators in SEA & P [10]. These observations suggest that several local governments should establish policies that create training opportunities for local staff with basic degrees to attain higher degrees. Staff salary enhancement strategies should also be considered to attract young skilled personnel and foster staff retention rates.

Limited use of modern biophysical tools to monitor and predict their spread was observed. Timely understanding of pathogens in terms of environmental conditions, transmission routes, and evolution biology enhance forecasting disease spread at plot, field, and landscape levels [17, 18]. Several multi-scale experiments using sensor systems, feature extraction and algorithms multiple scales have yielded significant results in remote monitoring of plant diseases and pests[19, 20, 21]. For instance, drone technology [22] and spectral image analysis [23, 24] has proved effective in spatial monitoring of emerging diseases. Yin and others recently demonstrated that phenotypic fluorescent probes could be used to monitor plant metabolic changes such as hydrogen peroxide, which are part of the defence signalling cascade induced by infection [21]. Such fluorescent probes, which can function without a skilled operator, could act as early predictors of disease-associated stress in plants. Machine learning has been used to predict cassava diseases associated with fungi, viruses, and bacteria [25]. These predictive tools could help accelerate surveillance of emerging TPPs in the region. However, they are costly and thus require decisive public investment in equipment and expertise. Governments in SEA and P must increase their annual agricultural spending to procure radiodiagnostic equipment and capacity building.

Existing infrastructure in the region is either ill-equipped or dilapidated. Stads and colleagues made similar observations in 2020 [10]. Dysfunction infrastructure stifles agricultural research innovations, and this problem is linked to low public expenditure on agriculture in SEA. For instance, several SEA countries

have had trouble characterising Fusarium wilt (tropical race 4) in bananas, greening disease in citrus and witches broom disease in cassava due to lack of necessary laboratory infrastructure. These diseases and many more continue to spread unabatedly between borders. There is a need to galvanise donors in the region and beyond to fund improving and resourcing local facilities with tools, equipment and trained human resource to run them. For the sustainability of such country-level facilities, establishing a state-of-the diagnostic laboratory to complement national diagnostic facilities is critical.

Finally, access to TPPs surveillance data should be increased. We observed gaps in the TPPs lists. In all countries surveyed, information on symptomology, incidence, severity, and impact of economically important Data on TPPs of major food and cash crops such as cassava, rice, and citrus was scanty or unavailable. There's a need to harmonise existing TPPs profiling protocols or develop them where they don't exist. Such efforts would result in a comprehensive TTP list to boost regional-level surveillance. TPPs lists can be validated periodically through surveys and focused group discussions with country surveillance teams. It is thus important to facilitate the formation of country- and regional-level surveillance task forces to champion this cause. Representatives from farming communities, private agribusinesses, departments of agriculture, border inspectorates, NPPOs and international research centres may constitute the task force. We further noted limited utilisation of available digital resources on invasive plant pathogens. Such a gap may limit effective TPP containment between countries. There is a need to engage with location institutions charged with TPP surveillance to utilise existing integrated and well-curated databases such as CABI, PestDisPlace curated by CIAT, The Global Pest and Disease database, and EPPO. This will enhance awareness of imminent biosecurity threats to crop production.

Links to online interactive resources:
First reports: https://pdptest.ciat.cgiar.org/report/sea/asia
Network: https://pdptest.ciat.cgiar.org/surveyFAO/results
Poll: https://pdptest.ciat.cgiar.org/surveyFAO

Acknowledgements
We are thankful to our colleagues and research partners in the Asia region and the whole Cassava Program team. CGIAR's Plant Health Initiative, the Australian Center for International Agricultural Research (ACIAR), and FAO, supported this work.

References

1. Ristaino, J. B., Anderson, P. K., Bebber, D. P., Brauman, K. A., Cunniffe, N. J., Fedoroff, N. V., Finegold, C., Garrett, K. A., Gilligan, C. A., Jones, C. M., Martin, M. D., MacDonald, G. K., Neenan, P., Records, A., Schmale, D. G., Tateosian, L., & Wei, Q. (2021). The persistent threat of emerging plant disease pandemics to global food security. *Proceedings of the National Academy of Sciences of the United States of America*, *118*(23). https://doi.org/10.1073/PNAS.2022239118/-/DCSUPPLEMENTAL
2. Rizzo, D. M., Lichtveld, M., Mazet, J. A. K., Togami, E., & Miller, S. A. (2021). Plant health and its effects on food safety and security in a One Health framework: four case studies. *One Health Outlook*, *3*(1). https://doi.org/10.1186/s42522-021-00038-7
3. Anderson, P. K., Cunningham, A. A., Patel, N. G., Morales, F. J., Epstein, P. R., & Daszak, P. (2004). Emerging infectious diseases of plants: Pathogen pollution, climate change and agrotechnology drivers. *Trends in Ecology and Evolution*, *19*(10), 535–544. https://doi.org/10.1016/j.tree.2004.07.021
4. FAO. (2008). Climate-Related Transboundary Pests and Diseases. *Technical Background Document From the Expert Consultation Held on 25 to 27 FEBRUARY 2008, ROME*, *February*, 59.
5. Baudron, F., & Liégeois, F. (2020). Fixing our global agricultural system to prevent the next COVID-19. Outlook on Agriculture, 49(2), 111-118.

6. Flood, J. (2010). The importance of plant health to food security. Food security, 2(3), 215-231.
7. Sikes, B. A., Bufford, J. L., Hulme, P. E., Cooper, J. A., Johnston, P. R., & Duncan, R. P. (2018). Import volumes and biosecurity interventions shape the arrival rate of fungal pathogens. *PLoS Biology*, *16*(5), 1–16. https://doi.org/10.1371/journal.pbio.2006025
8. Gupta, A. (2012). Pesticide use in South and South-East Asia: Environmental public health and legal concerns. *American Journal of Environmental Sciences*, *8*(2), 152–157. https://doi.org/10.3844/ajessp.2012.152.157
9. Willis, K. (2017). *State of the world's plants 2017*. Royal Botanics Gardens Kew.
10. Stads, G.-J., Pratt, A. N., Omot, N., & Pham, N. T. (2020). *Agricultural Research in Southeast Asia a Cross-Country Analysis of Resource Allocation, Performance, and Impact on Productivity*. https://doi.org/10.2499/P15738COLL2.134063
11. Seebens, H., Blackburn, T. M., Dyer, E. E., Genovesi, P., Hulme, P. E., Jeschke, J. M., Pagad, S., Pyšek, P., van Kleunen, M., Winter, M., & Essl, F. (2018). Global rise in emerging alien species results from increased accessibility of new source pools. *Proceedings of the National Academy of Sciences*, *115*(10), E2264-E2273.
12. Wan, F. H., & Yang, N. W. (2016). Invasion and Management of Agricultural Alien Insects in China. Annual Review of Entomology, 61, 77–98. https://doi.org/10.1146/annurev-ento-010715-023916
13. Wan, H., Wang, Q., Jiang, D., Fu, J., Yang, Y., & Liu, X. (2014). Monitoring the invasion of Spartina alterniflora using very high resolution unmanned aerial vehicle imagery in Beihai, Guangxi (China). Scientific World Journal, 2014, 14–16. https://doi.org/10.1155/2014/638296.
14. Hao, X., Wang, L., Zhang, X., Zhong, Q., Hajano, J. U. D., Xu, L., & Wu, Y. (2021). A real-time loop-mediated isothermal amplification for detection of the Wheat dwarf virus in wheat and the insect vector Psammotettix alienus. , PDIS-10. Plant Disease, PDIS-10.
15. Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., & Nelson, A. (2019). The global burden of pathogens and pests on major food crops. Nature ecology & evolution, 3(3), 430-439.
16. Bebber, D. P., Holmes, T., Smith, D., & Gurr, S. J. (2014). Economic and physical determinants of the global distributions of crop pests and pathogens. New Phytologist, 202(3), 901-910.
17. He, S., & Krainer, K. M. C. (2020). Pandemics of people and plants: which is the greater threat to food security?. Molecular plant, 13(7), 933-934.
18. Kreuze, J., Adewopo, J., Selvaraj, M., Mwanzia, L., Kumar, P., Cuellar, W. J., Legg, J.P., Hughes, D.P.& Blomme, G. (2022). Innovative digital technologies to monitor and control pest and disease threats in Root, Tuber, and Banana (RT&B) cropping systems: progress and prospects. Root, Tuber and Banana Food System Innovations, 261-288.
19. Lee, K. J., Kang, J. Y., Lee, D. Y., Jang, S. W., Lee, S., Lee, B. W., & Kim, K. S. (2016). Use of an empirical model to estimate leaf wetness duration for operation of a disease warning system under a shade in a ginseng field. Plant Disease, 100(1), 25-31.
20. Lee, G., Wei, Q., & Zhu, Y. (2021). Emerging wearable sensors for plant health monitoring. Advanced Functional Materials, 31(52), 2106475.
21. Yin, Y., Wang, G., Liu, Y., Wang, X. F., Gao, W., Zhang, S., & You, C. (2022). Simple Phenotypic Sensor for Visibly Tracking H2O2 Fluctuation to Detect Plant Health Status. Journal of Agricultural and Food Chemistry, 70(32), 10058-10064.
22. Tsouros, D. C., Bibi, S., & Sarigiannidis, P. G. (2019). A review on UAV-based applications for precision agriculture. Information, 10(11), 349.
23. Zhang, X., Han, L., Dong, Y., Shi, Y., Huang, W., Han, L., González-Moreno, P., Ma, H., Ye, H. & Sobeih, T. (2019). A deep learning-based approach for automated yellow rust disease detection from high-resolution hyperspectral UAV images. Remote Sensing, 11(13), 1554.
24. Yuan, L., Yan, P., Han, W., Huang, Y., Wang, B., Zhang, J., Zhang, H.. & Bao, Z. (2019). Detection of anthracnose in tea plants based on hyperspectral imaging. Computers and Electronics in

Agriculture, 167, 105039.
25. Ayu, H. R., Surtono, A., & Apriyanto, D. K. (2021). Deep learning for detection cassava leaf disease. In Journal of Physics: Conference Series (Vol. 1751, No. 1, p. 012072). IOP Publishing.

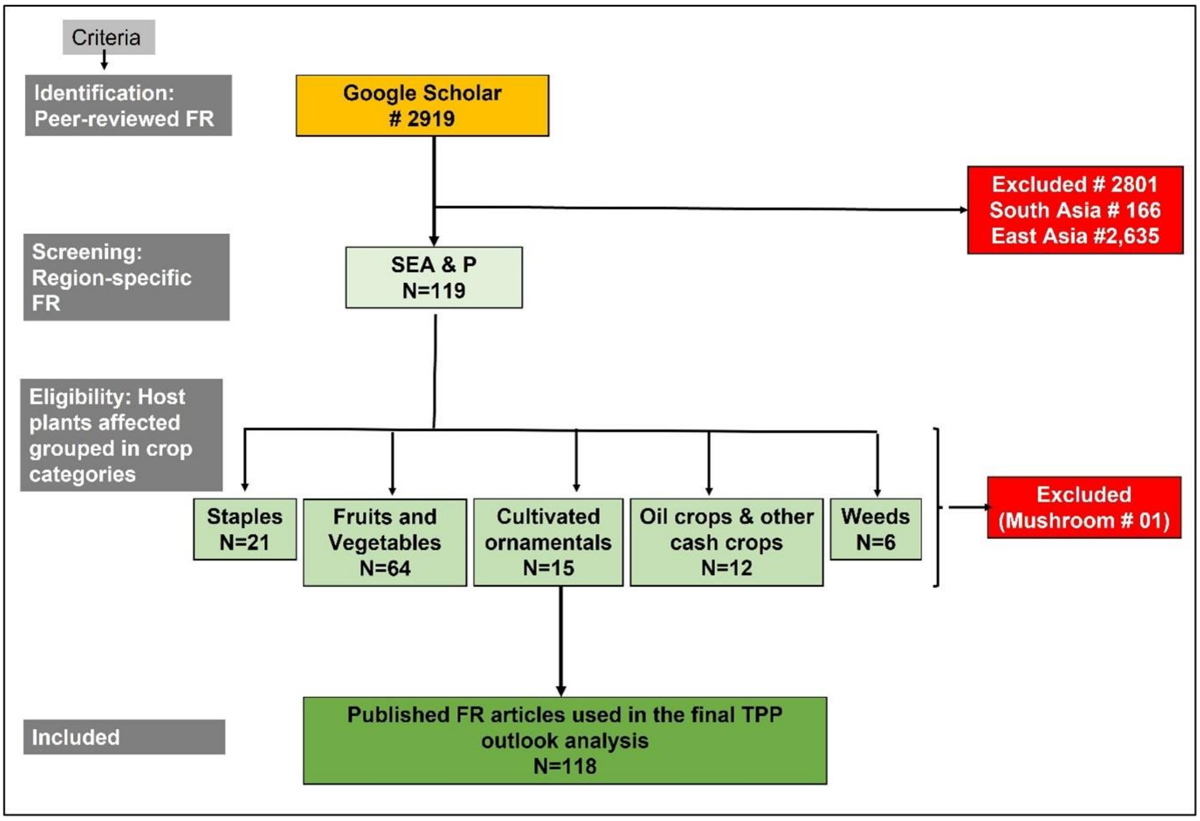

Figure 1. Flow diagram for selecting peer-reviewed articles included in this study. N symbolises number of articles, FR = First Reports, SEA & P = Southeast Asia and the Pacific.

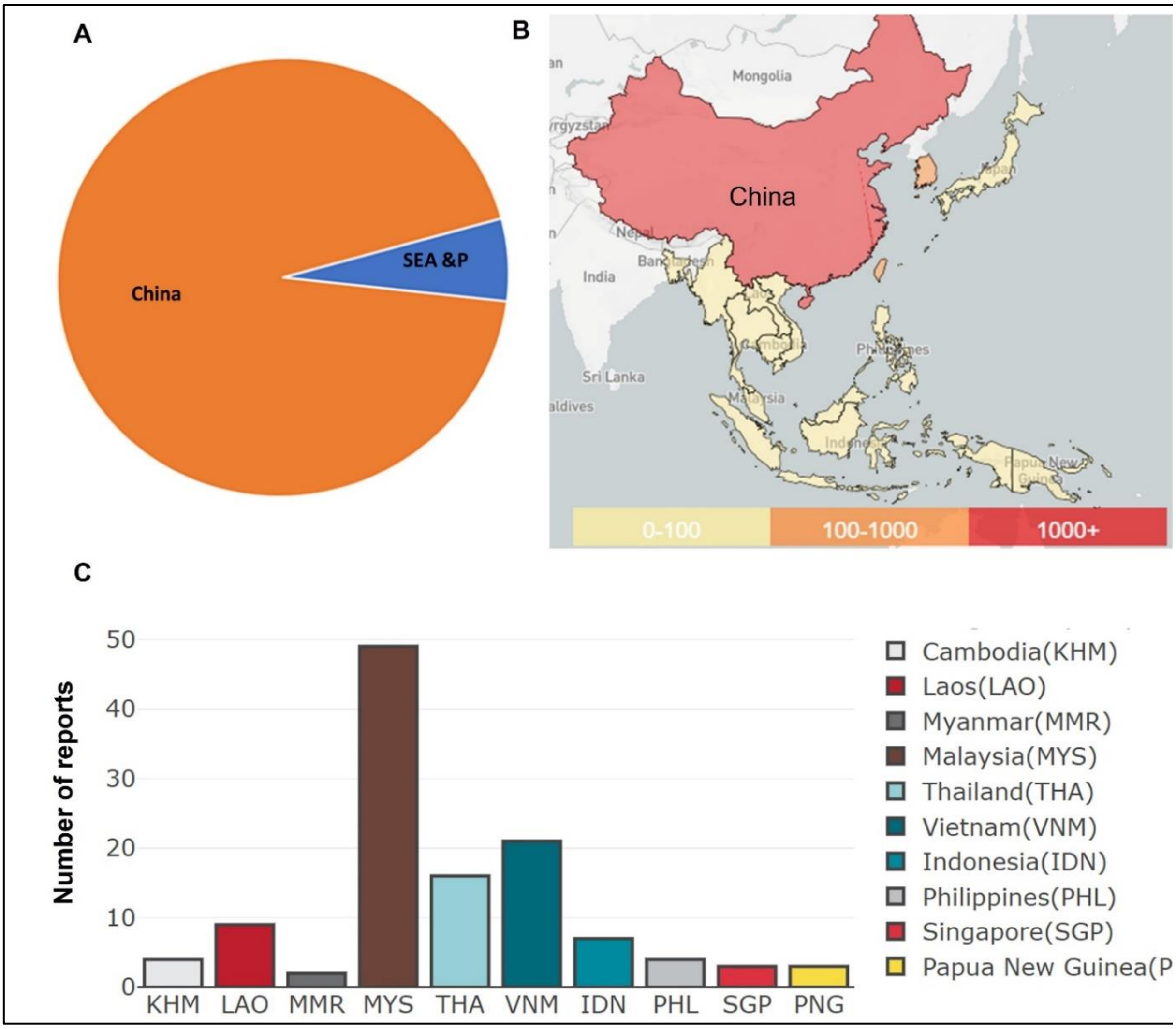

Figure 2. The status of TPP reporting in Asia between 2000 and 2021. A indicate total reports by China compared to SEA & P countries combined ; B shows the geographic distribution of TPPs reports, C indicate total TPPs peer reviewed from 10 SEA & P countries. The map was generated in MS Excel Map charts using Supplementary data S1.

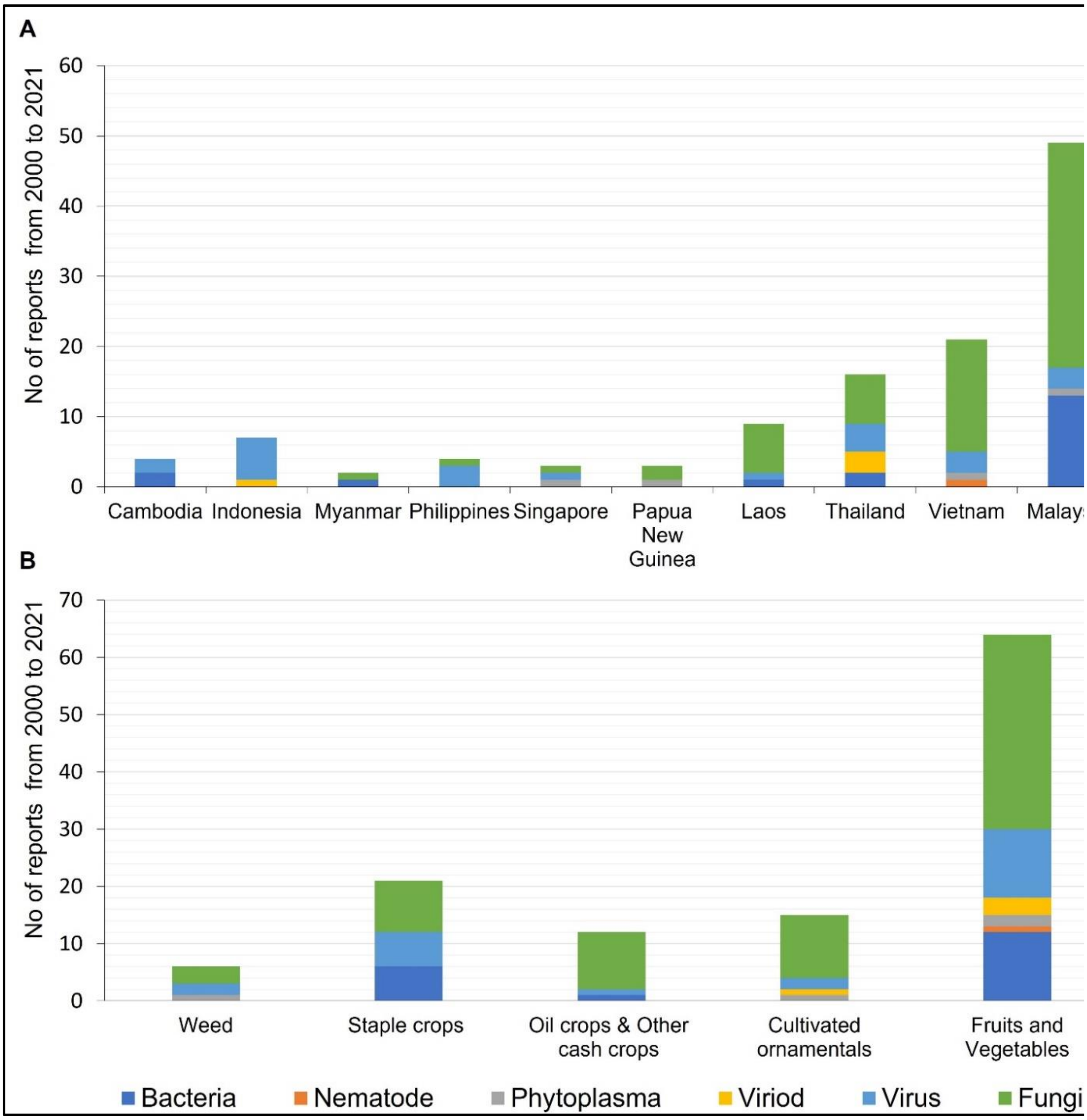

Figure 3. Reporting on specific TPPs causing economically significant impact changed between countries and host plants. The majority of peer-reviewed reports covered fungal pathogens compared to other pathogens. Infections caused by viruses and viroids were the least reported in the region. Most reports came from four out of ten countries (**A**). Comparison of reporting levels for each pathogen classification using Chi-square test showed between-country differences ($\chi 2$ =1885689, p= 0.0004). **B** shows the relationship between pathogen classes and plant hosts they infected. Fungi-associated TPPs were highest in fruits and vegetables and least in weeds. Reports of viruses and viroids were restricted to cultivated ornamentals and fruits and vegetables.

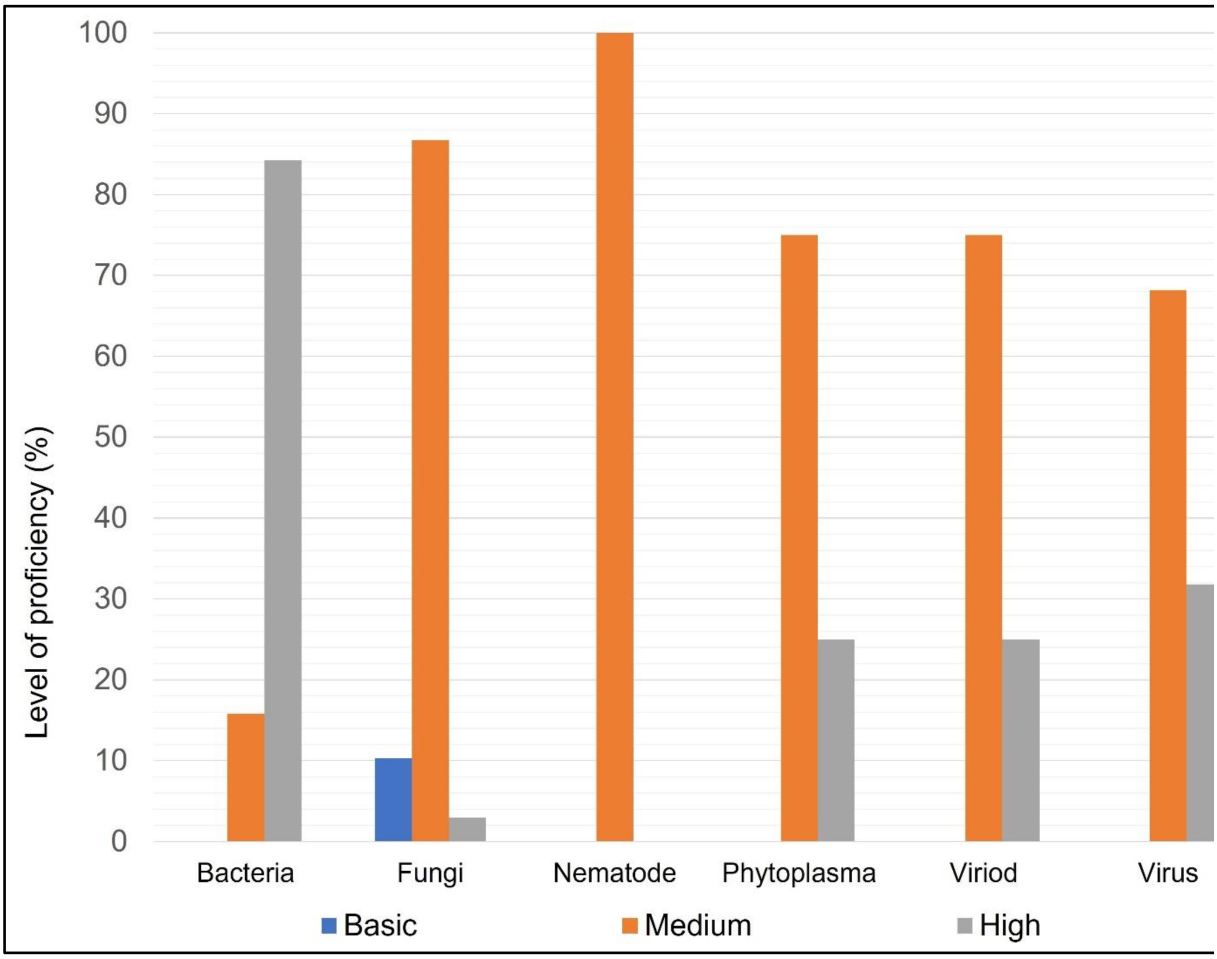

Figure 4. The level of expertise in identification and reporting of TPPs differed between pathogens. A high level of expertise was demonstrated in the analysis of bacterial pathogens. Basic methods such as the use of indicator plants and microscopy were mostly used to identify fungal-causing organisms compared to other pathogens.

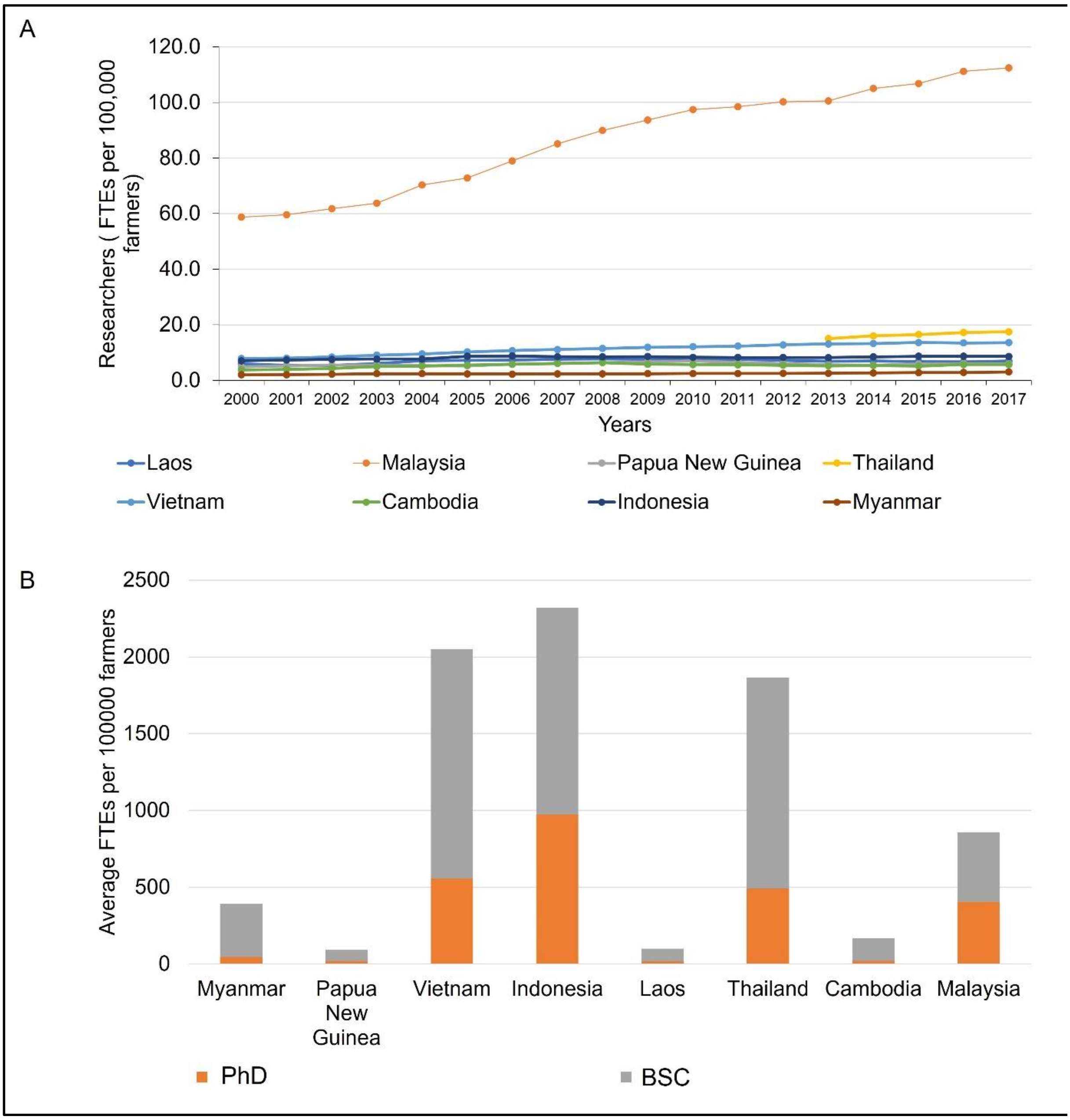

Figure 5. The graph showing FTEs of agricultural researchers (A) and FTEs by academic qualification (B). This data was obtained from the ASTI database. We also failed to get China data for comparison as a control group. This analysis excluded Singapore, the Philippines and China because data was unavailable.

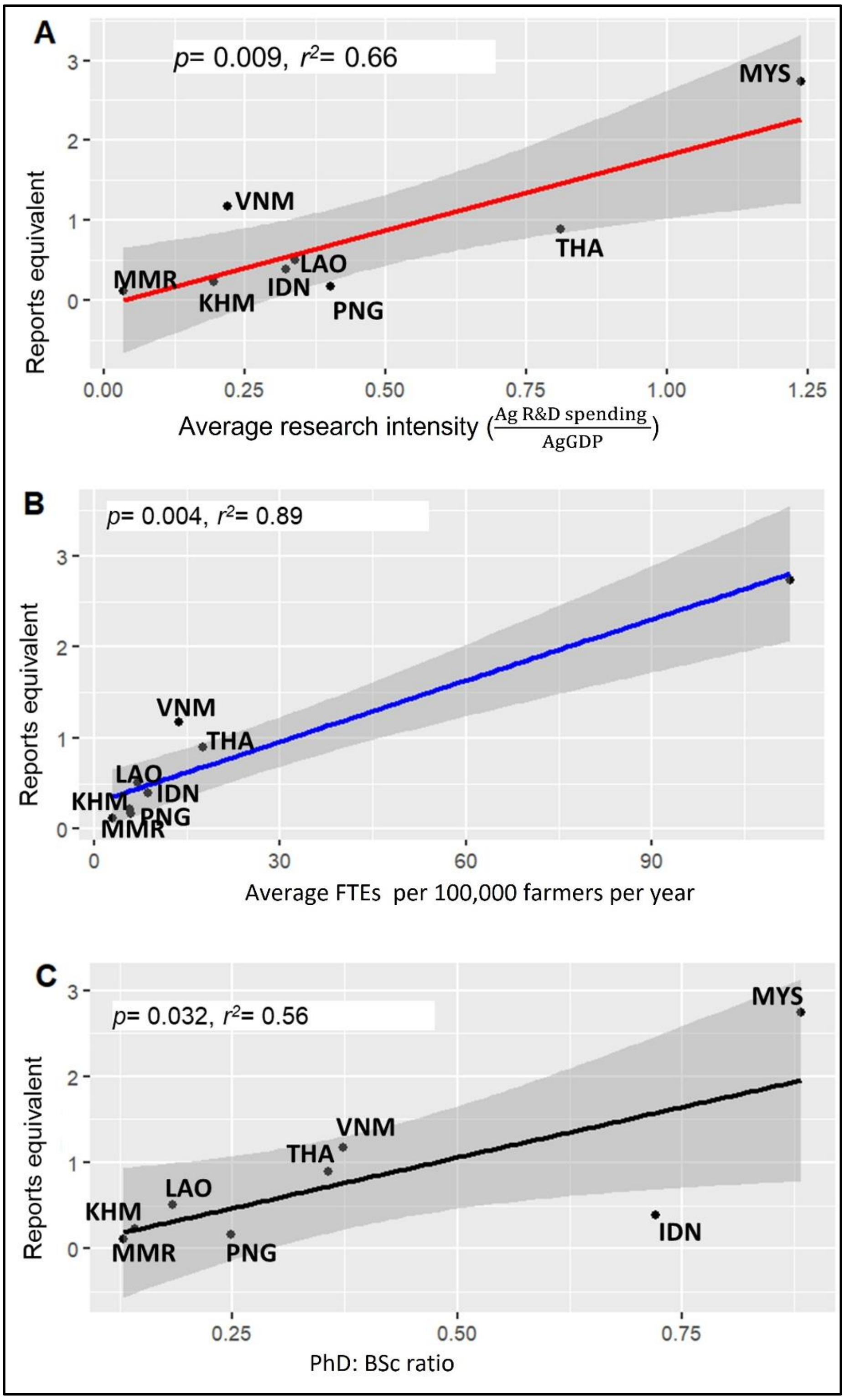

Figure 6. Potential drivers of TPPs reporting levels in SEA and the Pacific region. Research intensity (A), the number of FTEs per 100,000 farmers (B) and FTEs by qualifications expressed as a ratio of PhD: BSc holders per country (C) can be used to predict the level of TPPs reporting in SEA & P countries. The values on the y-axis indicate relative reporting per country, here referred to as reports equivalent, was calculated by dividing the total number of reports per country by the average FTEs per 100,000 farmers between 2000-2017 (17.9). Data from 2018-2021 was not available for comparison. The analysis also excludes Singapore, the Philippines and China. All statistics were generated using linear models in R statistics. Points represent countries (see Fig. 3 for abbreviations).

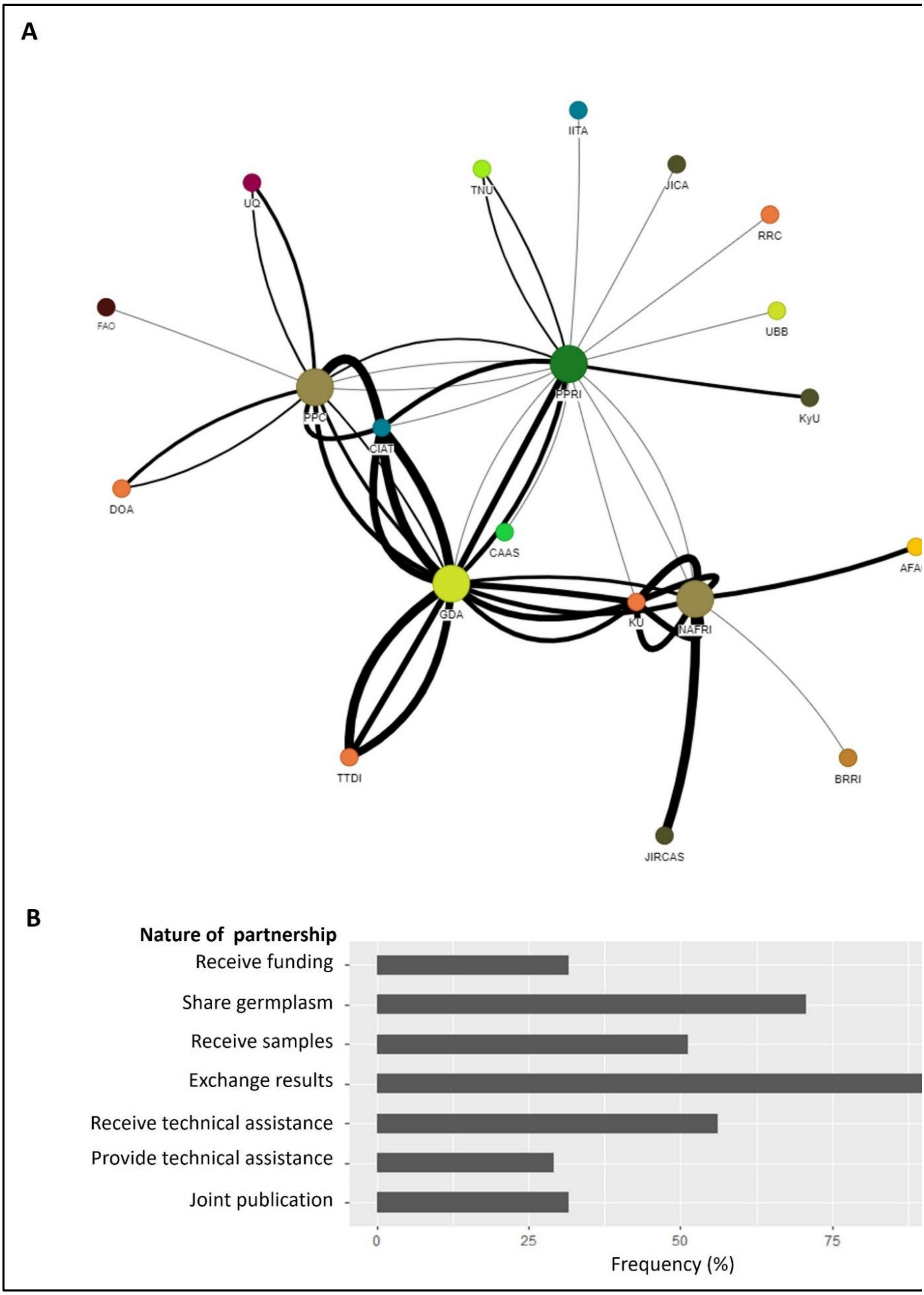

Figure 7. Collaborative linkages within and between countries to manage TPPs. In three countries of Cambodia, Vietnam and Laos, 22 partnerships were recorded as shown in A. **GDA**= Government Directorate of Agriculture; **PPRI**= Plant Protection Research Institute, **PPC**= Plant Protection Centre, **NAFRI**= National Agriculture and Forestry Institute- The Rice Research Centre,

RRC= Rayong Research Centre, **KU**= Kasetsart University, **UBB**= University of Battambang, **JICA**= Japan International Cooperation Agency, **KyU**= Kyushu University, CAAS= Chinese Academy of Agricultural Sciences, TNU= Taiwan National University, **DPP**= Department of Plant Protection, Cambodia, **DOA**= Directorate of Agriculture, **UQ**= University of Queensland, Australia, **FAO**= Food and Agriculture Organisation, **TTDI**= Thai Tapioca Development Institute, **IPBV**= Institute of Plant Breeding of Vietnam, **JIRCAS**= Japan International Research Centre for Agricultural Sciences, **BRRI**= Bangladesh Rice Research Institute, **AFACI**= Asian Food and Agriculture Cooperation Initiative, **IITA**= International Institute of Tropical Agriculture, and **CIAT**= International Centre for Tropical Agriculture. The size of the network connect represents partnership strength (A). Same-coloured nodes indicate that partners originate from the same country. The interactive network matrix can be found here. B shows the type of relationship different local, regional and global partners shared.

Table 1. TPPs identification proficiency matrix based on analytical methods in peer-reviewed papers

TPP Identification Method	**Tier**	**Proficiency level**
Morphological/ symptom analysis, indicator plants, microscopy for fungi)	Tier 1	Basic/low
Biochemical, serological analysis (ELISA and LFD))	Tier 2	Medium
Transmission electron microscopy (TEM) for viruses, Molecular-level analysis i.e. PCR, RT-PCR, AFLP, Conventional sequencing)	Tier 3	
High throughput sequencing (HTS)	Tier 4	High
Multiple Methods	Tier 2 +Tier 3 or Tier 2+Tiers 3+ Tier 4	

Table 2 : Current human resource capacity and infrastructure in different NPPOs in Cambodia, Vietnam and Laos

A. Agricultural research staffing	Institution			
Section	GDA (Cambodia)	PPRI (Vietnam)	NAFRI (Laos)	PPC (Laos)
Field	10-15	6-10	16-20	1-5
Laboratory	6-10	1-5	6-10	1-5
Data analysis	1-5	1-5	1-5	1-5
B. Physical infrastructure				
Greenhouse	2	5	1	2
Laboratory	1	5	4	4

Table 3: Distribution of major TPPs by crop and country

		Distribution		
Major crop	**TPP**	**Cambodia**	**Vietnam**	**Laos**
Cassava	CWBD	Localised	Widely distributed	Widely distributed
	CMD	Widely distributed	Widely distributed	Localised
	Cassava Bacterial Blight Disease	Localised	-	-
Rice	Tungro Virus Disease	-	-	Widely distributed
	Thrips	-	-	Widely distributed
Banana	Panama disease	-	Widely distributed	-
	Banana stem rot	-	Widely distributed	-
Citrus	Citrus greening disease	-	Widely distributed	-
	Citrus Tristeza Virus Disease	-	Widely distributed	-

Table 4: Surveillance technologies used to monitor, detect and characterise TPPs .

Surveillance component	Specific tool	Laos	Vietnam	Cambodia	China [12, 13, 14]
Field	Image processing: Smartphones and digital cameras	Available and in use	Available and in use	Available and in use	Available and in use
	GPS tracking	Available and in use	Available and in use	Available and in use	Available and in use
	Physical monitoring	Available and in use	Available and in use	Available and in use	Available and in use
	Insect traps (light- or pheromone-based)	Available and in use	Available and in use	Not available	Available and in use
	Immunodetection and Immuno printing techniques	Available and in use	Not available	Not available	Available and in use
	Ground Penetration Radar System	Available and in use	Not available	Not available	Available and in use
	Unmanned Arial Vehicles, e.g., Drones	Not available	Not available	Not available	Available and in use
	Hyperspectral imaging systems	Not available	Not available	Not available	Not validated
	Thermal cameras	Not available	Not available	Not available	Available and in use
	Molecular-based detection, e.g., Loop-mediated isothermal amplification	Used but outsourced	Used but outsourced	Used but outsourced	Available and in use
	Artificial Intelligence Alert Systems	Not available	Not available	Not available	Not validated
	MinION sequencing	Not available	Not available	Not available	Available and in use
Laboratory	Microscopy	Available and in use	Available and in use	Available and in use	Available and in use
	ELISA	Available and in use	Not available	Not available	Available and in use
	PCR	Available and in use	Available and in use	Available and in use	Available and in use
	Biochemistry for bacterial pathogens	Available and in use	Available and in use	Available and in use	Available and in use
	Sanger sequencing	Used but outsourced	Used but outsourced	Used but outsourced	Available and in use
	Next-generation sequencing	Not available	Not available	Not available	Available and in use

Available and in use | Not available | Used but outsourced | Not validated

Table 5: Innovation in TPPs control and management in surveyed SEA countries.

	Laos	Vietnam	Cambodia
Routine Field Surveillance	Bi-annual monitoring surveys especially for cassava and rice TPPs -Data is curated and uploaded on PestDisPlace (https://pestdisplace.org/), a public database for tracking TPPs spread at a regional and global level -**Outreach initiatives**, e.g. the Lao Cassava Association (LCA) together with DOA monitors and trains farmers existing and emerging TPP problems.	District level plant protection teams conduct periodic TPPs monitoring surveys and inform Plant Protection Departments (PPDs). PPDs determine the next course of action -Data is curated and uploaded on a public database	-TPP surveys are conducted once every production year -Data is curated and uploaded on a public database
Eradication	Based on surveillance assessment, eradication session with affected farmers or company are conducted and the course of action agreed upon. In case severe disease cases, burry or and burn method is used.	PPDs have crop-based eradication standard operating procedures for given threats. Some of the eradication measures include rouging and burning of infected fields	No definitive action
Breeding	Active breeding programs for major TPPs of cassava and rice exist.	-Promising tolerant lines are received from regional and international partners for on-station and on-farm multilocation assessments. On-farm trials are farmer-led and participatory -Accelerated cassava flowering by photoperiod extension with artificial red light technology.	Same as Vietnam, especially for cassava breeding against CMD

Clean seed production	-Tissue culture and tunnel seed production systems were installed recently with the support of CIAT - Community-based seed producers for cassava -On-station production of clean rice seed, which is sold to farmers - Public- Private Partnerships such the CLEAN (Creating Linkage for Expanded Agricultural Network) initiative to ramp up cassava seed multiplication and train farmers on clean seed production. The project is being implemented by the Winrock International in partnership with the Department of Agriculture, Ministry of Agriculture and Forestry, Lao PDR	Use hydroponic seed production systems - Community-based seed producers for cassava and citrus	-Use tissue culture and tunnel production systems for rapid seed multiplication - Community-based seed producers for cassava
Pest control	-Distribute integrated TPP management factsheets to farmers - Promote rice field flooding to control destructive pests - Drone-enabled chemical control of cassava and vegetable pests. The technology is being piloted by LCA. It is being piloted among farmers in Southern Laos	Not definitive action	-Recommend application of approved pesticides to control whitefly populations in cassava - use of cultural control methods